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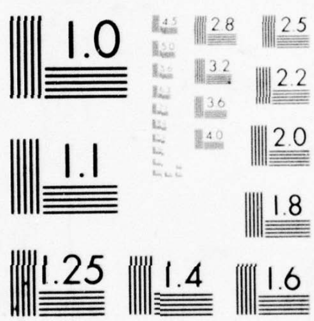

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Report No. FAA-RD-77-21

AREA NAVIGATION
ROUTE WIDTH REQUIREMENTS

A. R. STEPHENSON
W. H. CLARK

DECEMBER 1976

Final Report

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16. Abstract

This report presents the results of a study to determine if a requirement exists for reduced route widths in the National Airspace System. The basis for this investigation was the recommendation by the FAA/Industry RNAV Task Force that provision be made for constant and reduced route widths in order to handle the anticipated growth in air traffic by allowing more routes in the same airspace and less restriction on application of parallel offsets. The recommendation included a reduction of high altitude route widths from ±4.0 nm in the 1977-1982 period to ±2.5 nm in the post-1982 period. Route width requirements for both high altitude enroute and terminal areas are quantified, based on the impact of route width on route efficiency, airspace capacity, and route length. Results of this study, which are based on analysis of specific, high traffic demand geographical areas, indicate that there is a requirement to eliminate the current splayed route widths and provide constant width routes, but that there is no requirement for reduction of route widths below a constant ±4 nm in the high altitude enroute structure, or below the ±2 nm or ±4 nm, dependent upon distance from the VORTAC, which are currently required in the terminal area.

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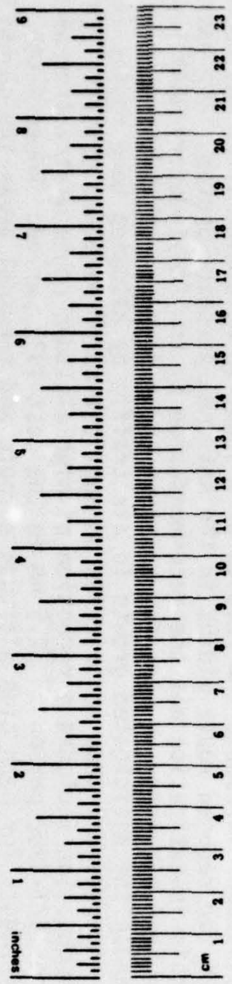
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

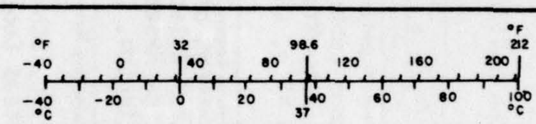
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The work described in this report was performed by the Aeronautical and Marine Systems Division (A&M) and the Champlain Technology Industries Division (CTI) of Systems Control, Inc. (Vt), a subsidiary of Systems Control, Inc., Palo Alto, California. The program was funded by the Federal Aviation Administration, under Contract No. DOT-FA72WA-3098. Mr. D.M. Brandewie was the FAA Technical Monitor and the Technical Support Program Manager was Mr. D. W. Richardson of CTI.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

The effectiveness of the Air Traffic Control System is dependent upon both route design and the ability of the controllers to establish an organized traffic flow within the constraints imposed by that design. The current system is based on procedural separation of routes, to the extent possible, with extensive use of radar vectors to provide separation during climb and descent and to resolve overtake and merge problems between aircraft enroute. One of the primary advantages of area navigation is the increased route design flexibility. This flexibility can be utilized to provide for a more efficient route structure in terms of major traffic flows, and it should also be utilized to reduce the system's dependence on radar separation to a much lower level than exists today. The FAA/Industry Task Force [1] envisioned that the system's dependence on radar could be reduced to primarily one of monitoring since a properly designed area navigation structure will greatly reduce the requirement for radar vectors. Inherent in the area navigation concept is the use of parallel routes and offsets with non-radar procedural separation. In order to provide this capability the Task Force recommended that constant route widths be utilized and that the capability to implement reduced route widths be provided. Specifically, enroute area navigation route widths were recommended to be reduced from the current ±4 nm with a splay of 3.25° to a constant ±2.5 nm in the post-1982 period. It was recommended that terminal area route widths be reduced from a constant ±2 nm (dependent upon distance from the VORTAC) to ±1.5 nm in the 1977-1982 period.

The purpose of the study described in this report was to organize the relevant data and perform analyses necessary to confirm or propose changes to these recommendations. Specifically, this study had the following objective:

- To determine if a requirement exists for reduced route widths, both enroute and in the terminal area, in order to provide for efficient route designs which will accommodate post-1982 traffic demand.

1.2 ENROUTE ROUTE WIDTH REQUIREMENTS

The current VOR structure is predicated upon route protection of ±4 nm out to a point 51 nm from the reference stations, with a 4.5° splay from 51 to 130 nm. This route width imposes a relatively significant constraint on the route designs, which manifests itself primarily in the number of routes which can be made available. The implementation of route structures based on smaller and constant route widths would potentially result in improved design efficiency, higher capacity, and shorter route lengths. The effect of route width on each of these factors was analyzed.

Two areas of enroute airspace, which were selected on the basis of high traffic density and complex route structure requirements, were analyzed to determine the impact of route width on design efficiency. The areas selected were a Pennsylvania area and an area east of Chicago. The current VOR structures were utilized to develop baseline RNAV structures, where the term "baseline" refers to the fact that the present accuracies and their corresponding route

widths are used. For each of the selected areas, this was accomplished by considering the current VORTAC coverage.

The coverage pattern of each area was constructed for several different coverage radius/route width combinations. A route width of ±4.5 nm was utilized for an analysis of design efficiency for the following reasons. It was noted that if ground support stations are used only to distances of 65 nm, then the ground stations for both the Pennsylvania and Chicago areas provide virtually complete area coverage. There is only one small area in Pennsylvania where adequate coverage is not available. Had smaller distances been utilized, many more coverage gaps would have been apparent and larger distances would have required additional route separation. The choice of the 65 nm coverage radius and the corresponding ±4.5 nm route width is not proposed as the optimal, but it does provide for the areas utilized in the analysis a very satisfactory balance between full station coverage and acceptably small route widths for the purpose of determining the input of route width on design efficiency.

Premised upon the ±4.5 nm route width, baseline RNAV route structures were created for both of the selected high density areas. The number of primary east/west routes through the Pennsylvania area was increased from 6 to 10 (67%) with a resulting increase in traffic capacity of far more than 67%, for the reasons discussed in Section 3.2.3. A few north/south routes were also added, but their quantity is basically unconstrained. A comparable increase in the number of routes was achieved in the Chicago area. It is for this reason that the benefits of a further reduction of route widths were not quantified. The increase in the number of routes which can be achieved through efficient RNAV implementation provides an increase in capacity far in excess of any projected increases in traffic. The incremental benefit of further route width reduction is expected to be so insignificant as not to be measurable.

One of the primary factors that led to the consideration of a reduced route width was the concern that traffic volume would grow to the point where available airspace would become saturated. The continued addition of VOR routes would eventually become laterally constrained with significant economic and safety implications. With today's navigational coverage patterns and restricted area locations, there appears to be only one area where this can become a significant factor in the high altitude airspace; this is the eastern approach to Los Angeles. Similar effects may exist elsewhere, but not with the same significance. With regard to the Los Angeles area, route width has the following direct effect on the high altitude movement of aircraft near restricted areas. The restricted areas laterally constrain the available airspace along a distance of approximately fifty miles. As examples, a route width of ±2.5 nm will allow five parallel routes to be designed; a route width of ±6 nm will allow only two routes. The effect of route width is manifested in the difference in the time, fuel and controller workload caused by traversing the 50 mile area when two routes are available as compared to five.

In order to estimate the differences in aircraft time and fuel, and controller workload, a computer program was developed to simulate air traffic movement. The route structure model utilized is a set of parallel enroute routes of 50 nm length. Three such structures were simulated consisting of three, four and five parallel routes with widths of ±4 nm, ±3 nm, ±2.5 nm,

respectively. The traffic data for the simulation was obtained from the FAA traffic projections for 1982 [2] and the peak hour traffic into and out of Los Angeles was determined.

The simulation consisted of randomly generating aircraft arrival times and using appropriate aircraft performance data to simulate their movement across the structure. Controller intervention was modeled so that this effect could be included in the simulation. The controller logic was based upon previous RNAV/controller experiments [3] and is considered representative of actual controller procedures in the geographical area being studied here.

The geographical area selected borders on the Los Angeles transition area. Transition-induced conflicts however, were not considered since it was the intent of this section to address enroute requirements. While most aircraft would ordinarily not be transitioning as far from the terminal as the simulated area, the Los Angeles traffic has several unusual characteristics which combine to produce an expanded effective transition region. This, in turn, causes an increase in conflicts. The study results are considered valid with regard to quantification of the effect of route width in an enroute environment. With respect to the specific simulated region, however, the absolute results may be biased as a function of the extent to which transition conflicts occur in the area.

The purpose of the conflict penalty assessment logic was to determine the aircraft time and fuel penalties and controller workload associated with or resulting from the fifty mile route structure being simulated. Penalties for conflicts are computed, based upon aircraft performance data derived for the same purpose as a part of the RNAV payoff analysis [3].

The simulations were conducted for three route structures (three, four, and five parallel routes) each with three levels of traffic, varying from 120% to 200% of the projected 1982 level. With the current navigation accuracies and the route design capabilities inherent with area navigation, three routes can be accommodated between the restricted areas bounding the eastern approach to Los Angeles, and the penalties for the three routes are sufficiently small that a constant ±4 nm route width in the enroute environment is concluded to be adequate from a capacity viewpoint. This conclusion is based on the use of this area to simulate a worst case enroute situation. The analysis of transition area route width requirements, particularly as epitomized by this unique area was beyond the scope of this study and was not included in the simulation. It is possible, however, that route widths less than ±4 nm may be required in a few transition areas such as that east of Los Angeles, particularly if increased joint use of restricted airspace, as recommended by the Task Force, does not occur.

Based upon the analyses performed to estimate the economic impact of RNAV [3], reduction in route length provides one of the more significant RNAV benefits. Since route width, under hypothetical circumstances, can affect route length by two percent or more, an analysis of this effect was considered important. A high altitude enroute RNAV route structure developed by NAFEC [4] was utilized in this analysis. The California corridor is the area where the NAFEC design best lends itself to a route length effects analysis, due to a high level of traffic and the fact that the relatively short overall route lengths serve to accentuate the significance when viewed on a percent basis. As a result, the California corridor was chosen as the area where the direct effects of route width on route length are maximum.

In order to determine the impact of route width on route length, several different route structures, based upon different route widths, were designed. The traffic forecasts developed by the FAA [2] and the design techniques inherent in the NAFEC design were utilized. The average per flight distance savings on a ±2.5 nm route width RNAV structure compared with the VOR structure was 4.96% of the VOR flight miles. Comparable per flight distance savings on a ±4 nm route width RNAV structure were 4.41% of the VOR flight miles. It was therefore concluded, based on this analysis, that a route width reduction from ±4 nm to ±2.5 nm was not warranted based on any benefit in reduced route length effects.

The results of these three analyses which investigated the impact of route width on design efficiency, capacity, and route length, all indicate that enroute route widths of a constant ±4 nm are adequate, and that reduction to a constant ±2.5 nm as recommended by the Task Force is not necessary. An analysis of the results of fast time simulations of traffic on a 429 airport pair RNAV structure designed by NAFEC [4] with ±4 nm route widths also indicated that projected post-1982 traffic could be efficiently accommodated without a reduction in route widths.

1.3 TERMINAL AREA ROUTE WIDTH REQUIREMENTS

Terminal area arrival capacity can be defined as the ability of the system to accommodate the necessary simultaneous approach paths and to deliver aircraft to the final approach fixes with minimum delay. Similarly, departure capacity can be defined as the ability of the system to accommodate the necessary simultaneous departure paths with a minimum of delay. Total capacity may then be defined in terms of establishing the optimum simultaneous mix of arrival and departure capacities.

The factors affecting terminal area capacity which may be expected to exhibit the greatest dependence on route width are:

- Availability of maneuvering airspace to achieve optimum sequencing

- Availability of airspace to accommodate an efficient terminal area design to meet anticipated traffic demand

In a related study [6] RNAV designs were created for seven major terminal areas. These designs initially were based on a ±1.5 nm route width for the post-1982 time period, as recommended by the Task Force. The designs were optimized through an iterative design/analysis procedure, based on both user economic and ATC impact considerations. In the course of this procedure, it was determined that route widths of ±2 nm and ±4 nm (dependent upon orientation and distance from the supporting VORTAC as currently required by AC 90-45A [9]) could be utilized with a negligible impact on user economics and the ATC system. Significant time and fuel savings were evident in the all-RNAV post-1982 design as compared with current VOR/radar vector routes [5], and the results of real-time simulations of the New York terminal area [7,8] indicated a significant reduction in controller workload, a substantial reduction in arrival operations delay, and an increase in arrival operations rates.

The results of the economic analysis and the real time simulations tend to confirm the overall efficiency of terminal area RNAV designs utilizing the route widths currently required. This section presents a summary of an analysis of the availability of maneuvering airspace required for sequencing in terminal areas with currently required route widths.

The approach utilized in the analysis was to develop a model relating delay maneuver geometry to sequencing distance requirements and to analyze specific terminal area designs for availability of the required airspace. The New York and Miami terminal areas were chosen for this study. The choice of New York was considered appropriate in view of the fact that three major airports exist in this area, and the severity of the maneuvering airspace requirement can be expected to equal or exceed that of any other. The New York terminal area design was based on constant ±2 nm route widths throughout, which are supported by VORTACs at the periphery of the terminal area where required. Miami was chosen as an example of a terminal area which is supported by only two VORTACs, both near the center of the terminal area, and whose routes are either ±2 nm or ±4 nm in width, according to the requirements of AC 90-45A [9].

A basic characteristic of the terminal area design is the provision for path shortening, or "corner cutting", by arriving aircraft. The primary concern here is to provide adequate airspace for path stretching maneuvers. For arrivals, terminal area route widths must support a converging capacity requirement where the goal is to accommodate arriving aircraft in a queue which will result in minimum allowable in-trail spacing at the final approach fixes. The approach used in analyzing the availability of airspace in which to adjust interarrival distance was as follows:

(1) Establish a set of "worst case" early arrival assumptions.

(2) Determine path stretching requirements for each route segment, based on the assumptions.

(3) Define a model relating delay fan geometry to sequencing distance requirements.

(4) Define delay areas for each route segment by plotting polygons in which the delay fan can be inscribed with a ±2 nm route width or a ±4 nm route width, dependent upon distance from the VORTAC.

(5) Determine if available path stretching capability meets or exceeds required capability.

Both the NE and SW flow designs for the post-1982 New York terminal area were analyzed to determine if sufficient airspace exists to accommodate departure passing routes and arrival maneuvering areas with the entire design based on route widths of ±2 nm. The fan areas were designed to provide procedural separation between JFK, LGA and EWR traffic. This was possible in all but two cases, and in neither of those cases was it possible to provide procedural separation through reduction in route width. The east flow design for Miami was selected as representative of terminal areas with route widths of ±2 nm

and ±4 nm, dependent upon distance from the VORTAC. An analysis of this design showed that sufficient airspace exists for the required maneuvering areas. The path stretching requirements used in these analyses were based on a set of assumptions. These requirements were verified by comparison with actual distances flown, over nominal, in a real-time simulation of the New York terminal area [8].

The results of the terminal area design effort [6], the user economic and ATC impact analyses [3,5], and the real-time simulations [7,8] indicated that there is no need for a reduction in the current route width requirements in the terminal area from the viewpoint of strategic design efficiency. The results of this analysis also indicates that there is no need for a reduction in route width to provide adequate airspace for tactical maneuvering. It was therefore concluded that terminal area designs utilizing current AC 90-45A route width requirements will accommodate the traffic demand projected for the post-1982 period, and that there is no requirement for the ±1.5 terminal area route widths recommended by the Task Force.

1.4 CONCLUSIONS

The major conclusions derived from this study are as follows:

1) Constant route widths, as opposed to the currently employed splayed routes, are required both enroute and in the terminal area to provide for the necessary design efficiency by allowing parallel routes and to maximize the use of non-radar procedural separation.

2) The RNAV Task Force recommended enroute route width of a constant ±4.0 nm in the 1977 time period is adequate to accommodate the post-1982 traffic, and a further reduction is not necessary.

3) The present terminal route width requirements given in AC 90-45A are adequate to accommodate the post-1982 traffic demand, and a further reduction in route width is not necessary.

2.0 ENROUTE ROUTE WIDTH REQUIREMENTS

The objective of this section is to determine if a requirement exists for reduced enroute route widths in the post-1982 time period. The question is addressed from two viewpoints: 1) the impact of route width on enroute design efficiency and airspace capacity and 2) the effect of route width on the economic impact of route length.

Two areas of enroute airspace, which were selected based upon high traffic density and complex route structure requirements, are analyzed. Route width is defined as the total width of the region about the route centerline which must be considered as part of the route. The route width is usually referred to by half of its total value preceded by "±". Thus, a ±4 nm route width implies that parallel route centerlines must be separated by a minimum distance of 8 nm.

2.1 HIGH ALTITUDE ENROUTE AREA SELECTION

Many variations of area selection criteria were considered. It was desired to find the enroute area whose design efficiency is impacted the greatest by route width. While the term "high density" has been used as the area descriptor, more factors than high density are involved. For example, when all aircraft are traveling in the same (or opposite) direction, most problems of high aircraft density can be solved by the addition of parallel routes. If, however, the route structure accommodating the traffic was already complex, the simple addition of routes could easily produce a structure of unmanageable complexity. More sophisticated route design procedures would be necessary and the extent to which they could be employed would directly impact route efficiency. The area selection criteria were, therefore, extended to include both density and complexity considerations.

There were four specific criteria utilized. Two of these relate to area complexity and two to area density. These are as follows:

<u>Area Complexity</u>:

1) Number of airport pairs whose great circle arcs intersect the area.

2) Daily traffic (number of aircraft) in area.

<u>Area Density</u>:

3) Peak aircraft density (aircraft per square mile).

4) Aircraft per great circle route mile.

While the first two measures above are very elementary, they are nonetheless the best indicators of route complexity. Each airport pair, regardless of its exchange, must be assigned a route. More airport pairs require more routes and when, for lack of airspace or area complexity, distinct routes for each cannot be made available, route lengths for some airport pairs are necessarily increased as the result of combining routes. The second measure is complementary, in that the significance of design inefficiency is proportional to the traffic volume affected.

The last two measures are density oriented. There were several alternate density measures which could have been used. An explanation as to why these specific measures were chosen is considered appropriate.

Any computation of aircraft density requires, as its foundation, the definition of a route structure and a traffic sample. In addition to the direct (great circle) structure, the route structures which could have been used include the current VOR structure and several hypothetical RNAV structures developed for related studies. The use of any "designed" structure, RNAV or VOR, would have led to results influenced by the peculiarities of the design. These extraneous influences were not considered desirable.

The use of the direct structure was not based upon its similarity to the preplanned environment, but rather because the direct structure projects a recognizable demand for airspace; when weather effects are ignored, these are the preferred flight paths.

The 1969 IFR Peak Day Tape was used as the traffic sample. IFR Peak Day Tapes are generated yearly by the FAA as a permanent record of traffic. For each U.S. Air Route Traffic Control Center (ARTCC), the tape contains information about every departing IFR flight which took place on the day when the ARTCC had the most traffic. Among other information, the following data is contained on the tape and was utilized in this study: origin and destination airport identifiers, requested departure time, anticipated true airspeed, and cruise altitude. Other tapes reflecting FAA traffic forecasts were available, but these forecasts do not contain all traffic and relate only to a five hour period.

The data base for the computation of the density measures was obtained from the IFR tape in the following way. Airport locations were determined for a data set of 330 airports. Every high altitude flight on the IFR tape (whose origin and destination airports were included in the data set) was simulated along the connecting great circle arc between the city pairs. The aircraft were assumed to fly at a constant speed (requested cruise true airspeed) for the entire flight. This assumption had the effect of positioning the aircraft farther along their paths than they would actually be, but it has no noticeable effect on traffic patterns or densities. The positions of each aircraft at each of 15 hours of the day were computed and recorded.

The "aircraft density" measure (criteria 3) was computed based on this data by simply calculating the number of aircraft per square mile. There are five definitions of the "aircraft per mile" measure (criteria 4). Each of these measures estimate the "average" number of aircraft per great circle route mile. The choice as to which individual measure was the most appropriate was not made and all five measures (described in Appendix B) were computed.

The computation procedure was as follows. For each time period, each route in the area was checked, and the number of aircraft on the route within the area was determined. The ratio of the number of aircraft to the route length interior to the area (aircraft per mile) was then computed. Altitude was considered so that each route actually consisted of several altitude separated paths. The density measures were then computed as the weighted average of these individual route statistics. The measures differ only in the weights assigned. The details of the density computations and the results are given in Appendix B.

The initial choice of a small number of candidate areas was a necessary step for selection simplicity. The selection criteria was then applied to choose two of these predefined areas for further analysis. It was decided that the most helpful tools in initial candidate area selection were scatter plots showing aircraft locations. These plots were generated based upon the traffic data described previously. The plots for each of the fifteen peak hours are given in Appendix A.

Seven areas were initially chosen. All of the areas were approximately 125 by 240 nautical miles. Standard size areas were used primarily to facilitate fair comparisons of the number of intersecting airport pairs and total traffic. The choice of this specific size, however, was subjective. The areas were large enough to encompass a major traffic/route design problem, but small enough to not be detrimental to the subsequent evaluation effort. The candidate areas were selected so as not to include major terminals, as terminal route width effects are treated separately. It was anticipated that the candidate areas should encompass the Golden Triangle Region*. This was distinctly validated by the plots. Figure 2.1 illustrates the areas overlayed on the scatter plot for 2300 GMT, the hour with the most total U.S. traffic. It can be seen that the areas selected cover essentially all regions of high density traffic.

Table 2.1 summarizes the density/complexity evaluation results, the details of which are given in Appendix A. Note that the California areas (6 and 7), while not ranking very high in the complexity criteria (i.e., overall density within the selected area is not very high), do rank high in density due to the high traffic flow over relatively few routes. These areas are not considered in this part of the analysis since each is considered elsewhere in this report.

The two areas selected for further analysis were the Pennsylvania area (#1) and the area to the east of Chicago (#3). These two areas ranked first and third in the number of intersecting airport pairs. They ranked first and second in both daily traffic and peak aircraft per square mile. With the exception of the California areas, only the area to the west of Chicago (#5) had more aircraft per route mile. Appendices A and B provide more detailed justification for the selection of these areas.

2.2 IMPACT OF ROUTE WIDTH ON DESIGN EFFICIENCY IN THE SELECTED HIGH DENSITY AREAS

The next step was to determine if reduced route widths (less than the current ± 4 nm plus splay) are required in the selected areas to accommodate projected traffic levels. The term "required" in this context is in need of further and explicit definition. An inadequate or inefficient route structure imposes penalties upon the ATC system operators and the airspace users. Whether or not these penalties warrant (impose a "requirement" for) an improved structure is a direct function of their severity. In order to avoid an arbitrary

*Region contained within the triangle whose vertices are New York City, Chicago and Atlanta.

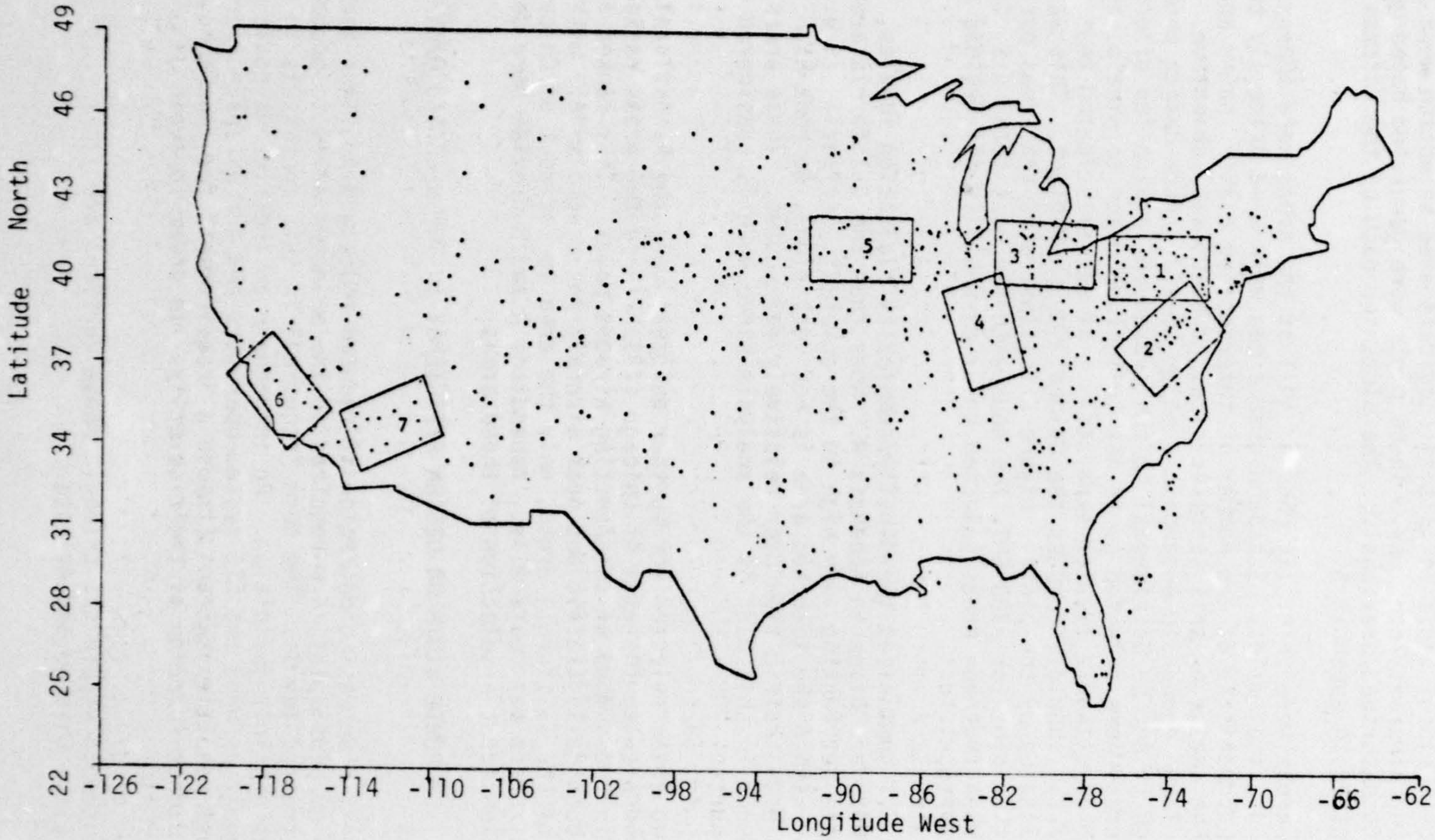


Figure 2.1 Scatter Plot With Candidate Areas For Evaluating Aircraft Density

Table 2.1
Enroute Area Density Evaluation Results

Area Location	No. of Airport Pairs	Daily Traffic	Peak Number of Aircraft Per Square Mile	Average of Route Density Measures (Aircraft per Mile)
1. Pennsylvania	344	1,803	.00161	.00926
2. Southwest of New York City	306	1,309	.00120	.00252
3. East of Chicago	284	1,697	.00154	.00659
4. South of Chicago	196	711	.00054	.00613
5. West of Chicago	114	786	.00083	.01046
6. California Corridor	79	759	.00058	.00803
7. East of Los Angeles	91	743	.00077	.01053

definition as to what level of penalties dictate structure improvement, it would be appropriate to conduct a cost/benefit study to determine if the costs of structure improvement, increased avionics and ground support accuracies, in particular, are outweighed by the benefits they produce. While such a study was only subjectively conducted as a part of this effort, this concept was, nonetheless, the driving force behind the analysis which was performed. For reasons which will later be explained, a detailed cost/benefit study would not have produced meaningful results.

The current VOR structure is predicated upon route protection of ±4 nm out to a point 51 nm from the reference station, with a 4.5° splay from 51 to 130 nm. This route width imposes a relatively significant constraint on the route designs, which manifests itself primarily in the number of routes which can be made available. The implementation of route structures based on smaller route widths would potentially result in the following advantages:

- shorter route lengths because more routes can be made available and can be more efficiently located
- fewer conflicts* (primarily overtakes) because the aircraft can be distributed among more routes, and
- the provision of more frequent optimum altitude assignments by virtue of the availability of additional routes

*In the high altitude regime, a conflict is defined as the simultaneous violation of horizontal separation requirements (5 nm) and vertical separation requirements (1000 ft at or below flight level 290, 2000 ft otherwise) by two or more aircraft.

The quantification of the requirements for reduced route widths relative to these benefits within high density areas can be accomplished through the following three steps:

- Analyze the current VOR structure to determine the general design techniques appropriate for this area
- Alter this structure, as necessary, to reflect the projected 1982 traffic level and the implementation of RNAV. Utilize the result as the baseline structure for the study
- Obtain an "improved" structure from the baseline by utilizing the additional flexibility afforded by a reduced route width

A preliminary analysis of the current structures*, shown in Figures 2.2 and 2.3, revealed that the third step above was not needed to provide an efficient design. The average route separations achieved in the VOR structures are significantly above ±4 nm. The structures can, of themselves, be so greatly improved with the assistance of RNAV design capabilities and constant route widths that further analysis regarding reduction of route width did not appear warranted.

The second step in this portion of the study was to utilize the current VOR structures to develop baseline RNAV structures, where the term "baseline" refers to the fact that the present accuracies and their corresponding route widths are used. For each of the selected areas, this was accomplished by considering the VORTAC coverage. For any specific range limitation (coverage radius), the porportion of the area which has adequate coverage can be determined. Larger radii logically lead to more complete coverage, while smaller radii potentially result in coverage gaps. Since the selected areas are free from terrain obstructions which impact coverage, the term coverage gap refers to too small a coverage radius rather than the absence of coverage. A small coverage gap can be traversed, although with an assumed increase in route width.

The coverage pattern of each area was constructed for several different coverage radii/route width combinations. A route width of ±4.5 nm was utilized for an analysis of design efficiency for the following reasons. It was noted that if ground support stations are used only to distances of 65 nm, then the ground stations for both the Pennsylvania and Chicago areas provide virtually complete area coverage. This coverage is illustrated in Figures 2.4 and 2.5. There is only one small area in Pennsylvania (shaded region in figure) where adequate coverage is not available. Had a smaller distance been utilized, many more coverage gaps would have been apparent and larger distances would have required additional route separation. The choice of the 65 nm coverage radius and the corresponding ±4.5 nm route width is not proposed as the optimal, but it does provide, for the areas utilized in the analysis, a very satisfactory

*Taken from "United States Government Flight Information Publication: Enroute High Altitude-U.S.", 23 May 1974

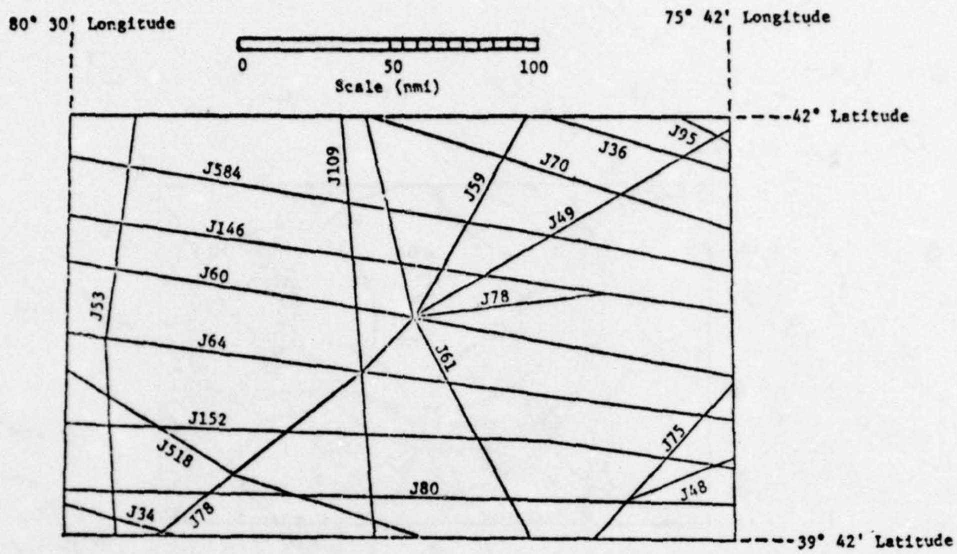


Figure 2.2 Current VOR High Altitude Structure for the Pennsylvania Area

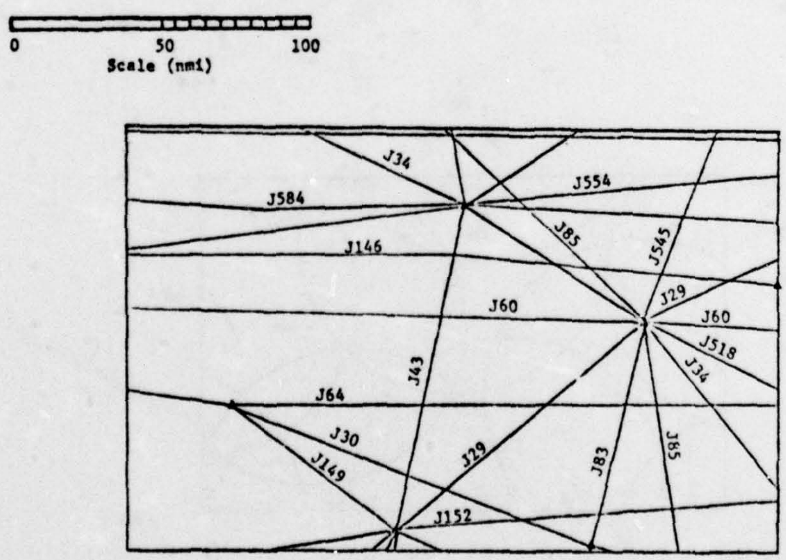


Figure 2.3 Current VOR High Altitude Structure for the Area East of Chicago

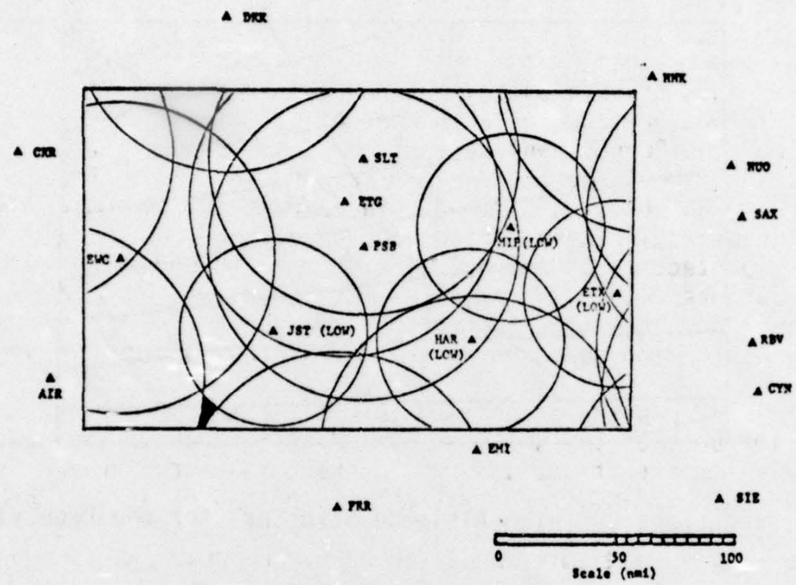


Figure 2.4 Current Station Coverage Based on a ±4.5 nm Route Width (65 nm Range, 40 nm Range for Low Altitude Stations) for Pennsylvania Area

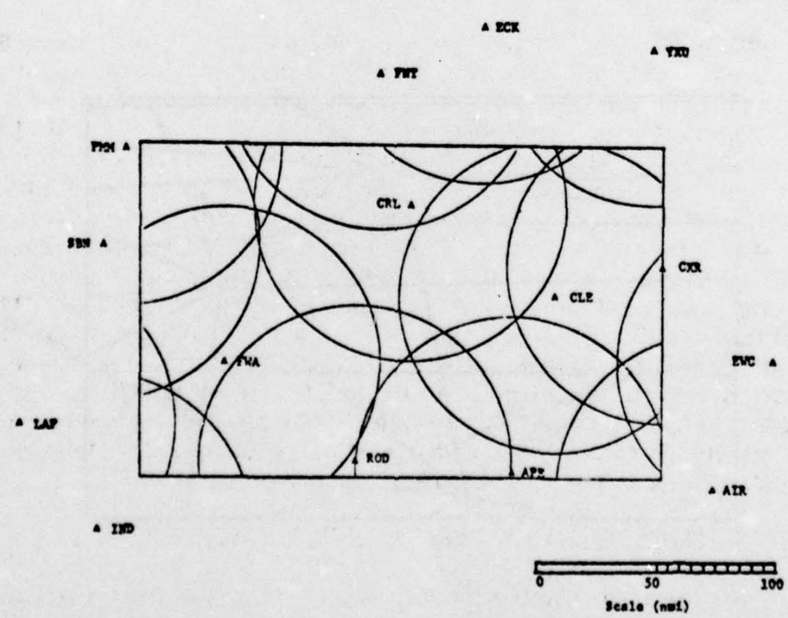


Figure 2.5 Current Station Coverage Based on a ±4.5 nm Route Width (65 nm Range) for the Chicago Area

balance between full station coverage and acceptably small route widths for the purpose of determining the impact of route width on design efficiency. The choice of 65 nm/±4.5 nm route width is based on utilization of current navigation accuracies. If it were assumed that some improvements would take place, as recommended by the Task Force, the 65 nm radius would easily support a smaller route width than the Task Force proposed ±4.0 nm for the 1977 time period with no increase in the number of coverage gaps in the two selected areas. For the Pennsylvania area, four low altitude VORTAC stations were utilized to supplement the coverage. The coverage radii in each case was assumed to be 40 nm, which is consistent with current low altitude VOR range regulations. Two of these stations are already a part of the high altitude jet route network. Frequency protection and signal accuracy is, therefore, assured. The frequencies of all stations within 250 miles of the other two low altitude stations were scrutinized and it was confirmed that the use of these two stations for high altitude navigation would not lead to frequency protection problems.

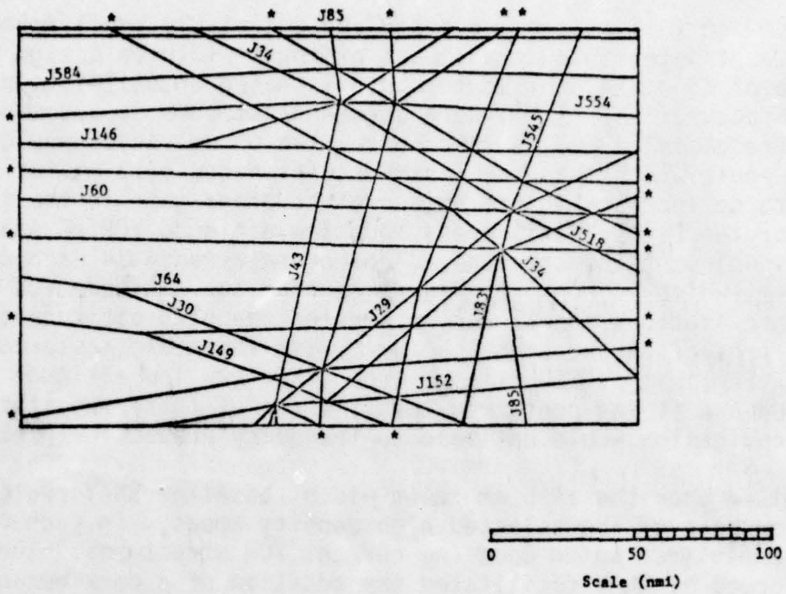
Premised upon the ±4.5 nm route width, baseline RNAV route structures were created for both of the selected high density areas. In each case, these structures were designed based upon the current VOR structures. The reduced route width afforded by RNAV facilitated the addition of a considerable number of routes. In certain cases the VOR routes were moved slightly to allow more efficient use of the airspace. In other instances, certain complex intersections were redesigned to provide a more organized structure. The RNAV designs are shown in Figures 2.6 and 2.7. It should be noted that every non-intersecting route segment is separated from its neighbors by at least 9 nm. Thus, the required route separations have been maintained. Further, with appropriate station selection, in no instance need the station changeover points be separated by less than 50 nm.

The purpose of developing the hypothetical RNAV designs was to obtain baseline structures which utilize the current RNAV navigation accuracies to their full potential. It can be seen that the number of primary east/west routes through the Pennsylvania area has been increased from 6 to 10 (67%). The resulting increase in traffic capacity is far more than 67%, for the reasons discussed later in Section 2.3. A few north/south routes were also added, but their quantity is basically unconstrained. A comparable increase in the number of routes was achieved in the Chicago area. It is for this reason that the benefits of a further reduction of route widths were not quantified. The increase in the number of routes which can be achieved through efficient RNAV implementation provides an increase in capacity far in excess of any projected increases in traffic. The incremental benefit of further route width reduction is expected to be so insignificant as not to be measurable. It should be noted, however, that extensive use of parallel RNAV routes was required, which results in a requirement for constant route widths as opposed to the current 3.25° splayed beyond 51 nm from the VORTAC.

2.3 EFFECT OF ROUTE WIDTH ON ENROUTE AIRWAY CAPACITY

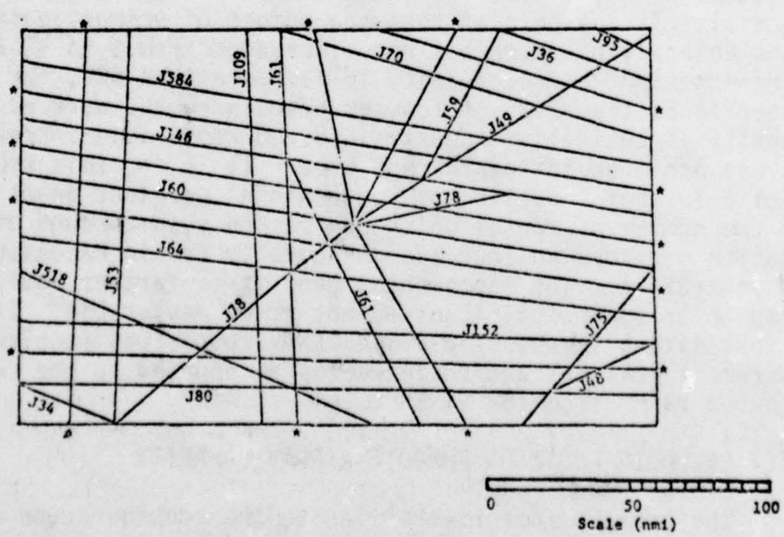
One of the primary factors that led to the consideration of a reduced route width was the concern that traffic volume would grow to the point where available airspace would become saturated. The continued addition of VOR routes would eventually become laterally constrained with significant economic implications.

With today's navigational coverage patterns and restricted area locations, there appears to be only one area where this can become a significant factor



(* Denotes additional RNAV routes over current VOR design)

Figure 2.6 Hypothetical RNAV Design for the Chicago Area



(* Denotes additional RNAV routes over current VOR design)

Figure 2.7 Hypothetical RNAV Design for the Pennsylvania Area

in the high altitude airspace; this is the eastern approach to Los Angeles (Figures 2.8 and 2.9). Similar effects may exist elsewhere, but not with the same significance. Quantification of the impact of lateral constraints on airspace is important for several reasons. First, if reduced route widths are deemed necessary, their implementation may result in the creation of navigational coverage gaps (due to increased VOR accuracy requirements). This will have the same impact on route width requirements as restricted areas. Also, the impact on the users and the FAA of restricted areas and coverage gaps has not been fully studied. This will become a critically important issue when low altitude traffic is considered. While this study does not address the problems of low altitude routes, several important results relevant to this issue are obtained.

Capacity, in general, usually implies the "maximum quantity which can be accommodated". With regard to air traffic, the aircraft in-trail separation requirements are the only factors which impose an absolute bound on the maximum number of aircraft. The absolute capacity of a system of routes in a high altitude enroute environment, however, cannot be measured by aircraft in-trail separation alone.

The capacity estimation methodology developed for this study uses times, fuel and workload factors as additional capacity or system performance measures. The definition of absolute upper bounds on these workloads or penalties has been avoided. In an enroute environment, capacity trade-offs always exist, and the results are presented herein with this in mind.

The overall context of this study is to identify and quantify the requirement, if any, for reduced route widths in an RNAV environment. One measure of the realism of this requirement is the evaluation of the impact on such operational criteria as flight time, fuel, and controller workload which is caused by restrictions on lateral airspace and the manner in which this impact differs as a function of the route width. By referring to Figure 2.9, it is obvious that the available lateral airspace places an upper bound on the product of route width and the number of routes. Further, it is logical that increasing the number of routes, by means of reducing the route width, increases the airway capacity. The provision of increased capacity, however, can only be properly evaluated when its effect upon economic factors can be quantified.

With regard to the Los Angeles area, route width has the following direct effect on the high altitude movement of aircraft through the restricted areas. The restricted areas laterally constrain the available airspace along a distance of approximately fifty miles. As examples, a route width of ±2.5 nm will allow five parallel routes to be designed; a route width of ±6 nm will allow only two routes. A structure with five routes would result in fewer aircraft per route and, therefore, fewer aircraft conflicts (overtakes). At some point, the routes must merge onto the final approach (or initial departure) segments. Smaller route widths, and consequently more routes, will allow the arriving aircraft to remain on less heavily traveled routes for a longer period of time and departing aircraft to demerge on less dense routes earlier in their flight. It can be assumed that the impact on the controller and the aircraft caused by the route merging is roughly the same whether the merging takes place to the east or the west of the restricted areas. The effect of route width in the above example is simply the difference in the time, fuel and controller workload caused by traversing the 50 mile area when two routes are available as compared to five.

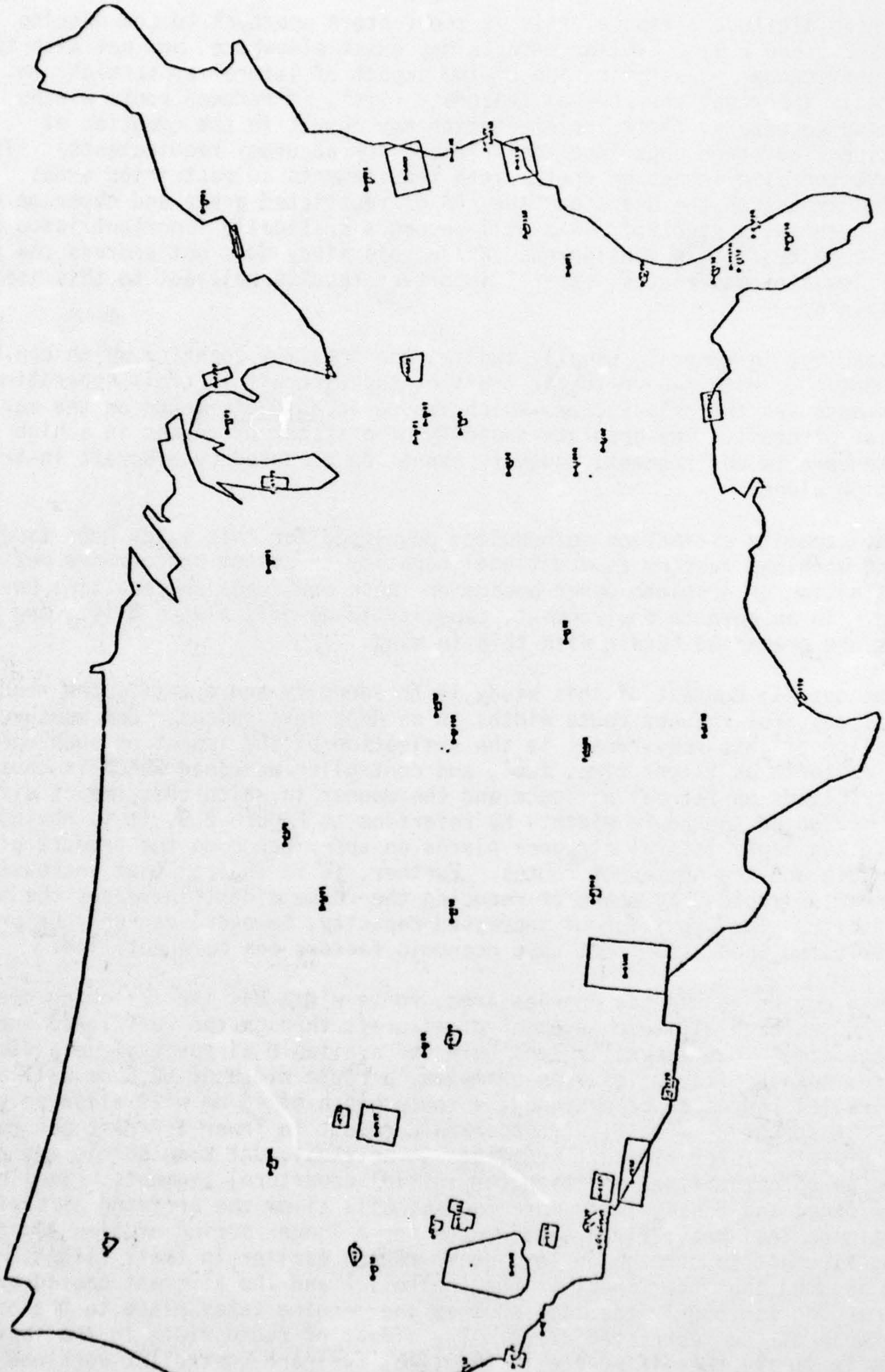


Figure 2.8 U.S. Restricted Areas

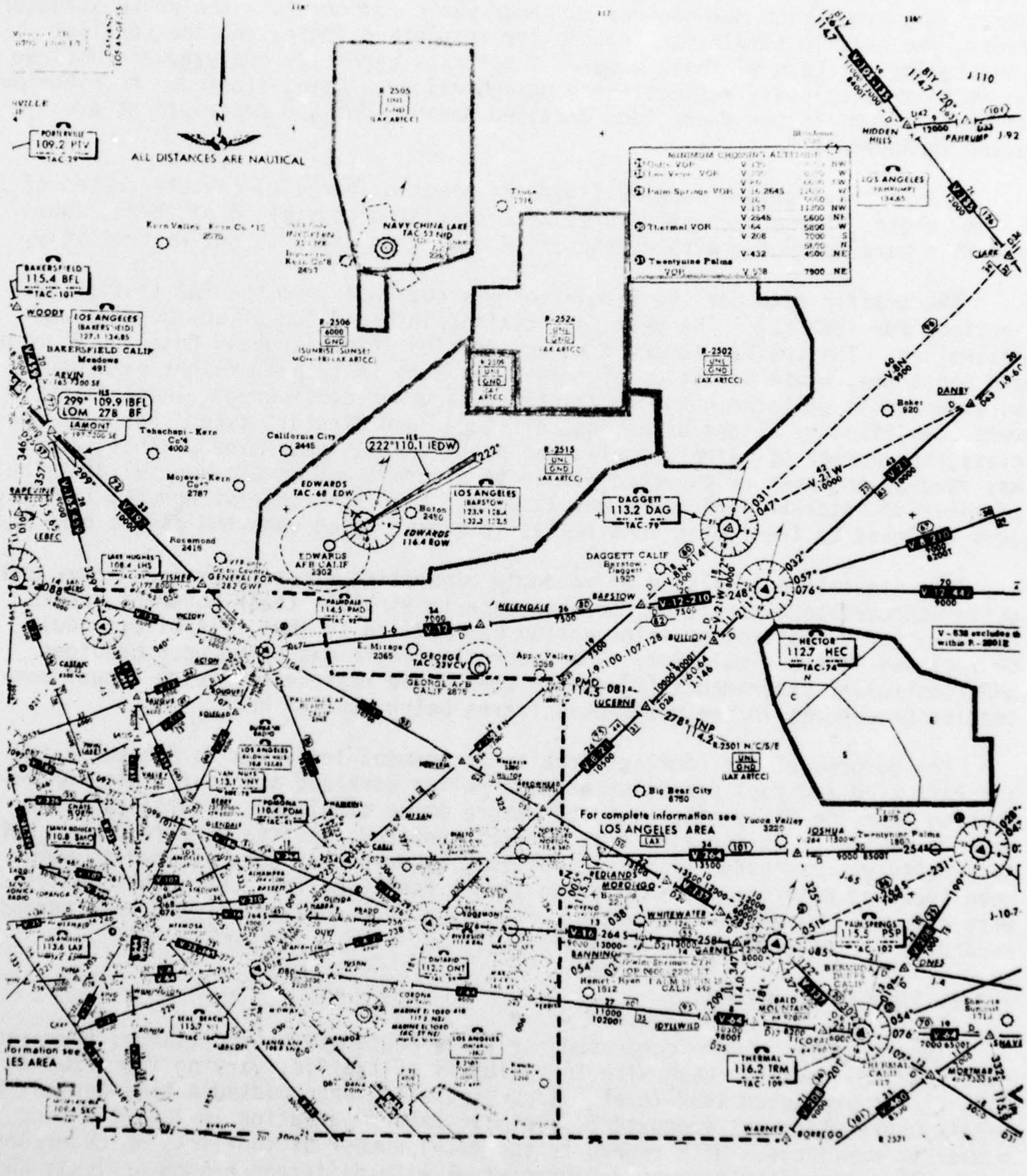


Figure 2.9 Eastern Approach to Los Angeles

2.3.1 Airway Capacity Estimation

In order to estimate the differences in aircraft time and fuel, and controller workload, a computer program was developed to simulate air traffic movement. The simulation methodology has four basic components: the route structure model, the traffic sample, the controller resolution logic, and the conflict penalty logic. Each of these program inputs was carefully analyzed and defined so as to realistically reflect the geographical area being studied. An overview of these inputs is now presented; detailed derivations and descriptions are given in Appendix C.

The route structure model utilized is a set of parallel enroute routes of 50 nm length. Three such structures were simulated consisting of three, four and five parallel routes with widths of ±4 nm, ±3 nm and ±2.5 nm, respectively.

The traffic data for the simulation was obtained from the FAA traffic projections for 1982 [2]. The peak hour traffic into and out of Los Angeles was determined. The traffic to and from Los Angeles International, Ontario, Burbank and Santa Ana, whose direction of travel was such that their flight path would be expected to go between the restricted areas, was considered. These flights were classified by flight direction, altitude, and aircraft type. For each such class, the number of flights during the peak hour was determined. This value was used as the mean or expected number of aircraft and an exponential distribution of aircraft inter-arrival times was assumed. For each route structure, the flights were assigned to the routes in a realistic manner based upon the flight direction.

The simulation consisted of randomly generating aircraft arrival times and using appropriate aircraft performance data to simulate their movement across the structure. Controller intervention was modeled so that this effect could be included in the simulation. The controller logic was based upon previous RNAV/controller experiments [2] and is considered representative of actual controller procedures in the geographical area being studied here.

The purpose of the conflict penalty assessment logic was to determine the aircraft time and fuel penalties and controller workload associated with or resulting from the fifty mile route structure being simulated. Conflicts which were in existence at the time that aircraft entered the area were resolved, but no penalty was assessed for these conflicts because they were assumed to have been incurred prior to the simulation time. Penalties for subsequent conflicts were computed, based upon aircraft performance data derived for the same purpose as a part of the RNAV payoff analysis [3].

2.3.2 Simulation Results

The simulations were conducted for three route structures (three, four and five parallel routes), each with three levels of traffic, varying from 120% to 200% of the projected 1982 level. Each simulation encompassed a time period of twenty hours which was adequate to minimize random variation in the resulting number of conflicts. With regard to the total number of conflicts which occurred, very little variation between different runs with different random arrivals and departures was observed. These data are, therefore, considered reliable. A plot of the average number of conflicts per hour is given in Figure 2.10.

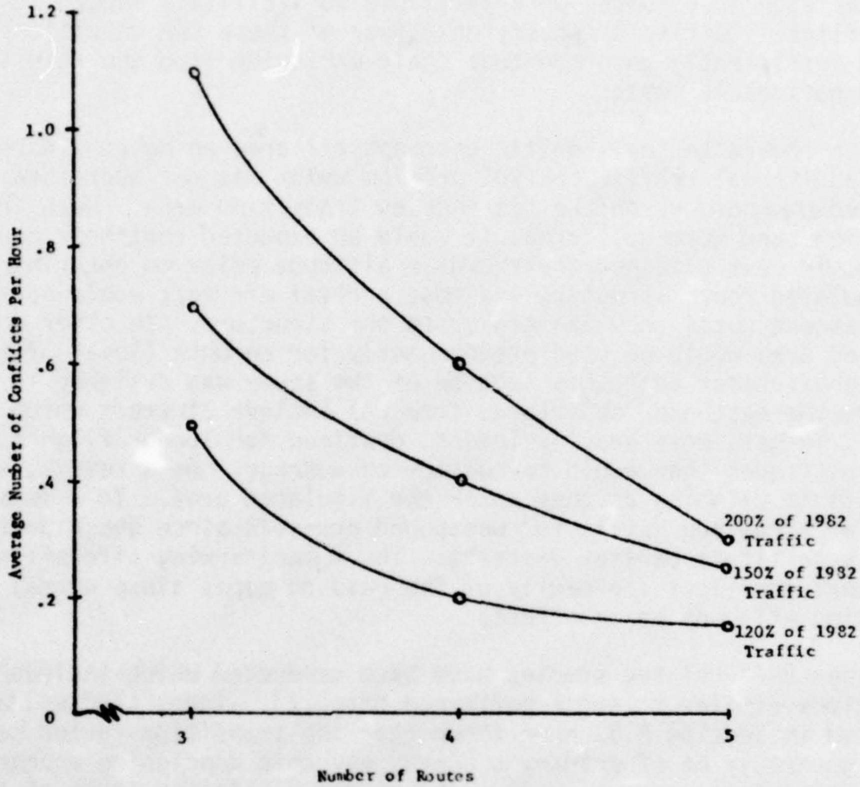


Figure 2.10 Average Number of Conflicts Per Hour as a Function of the Number of Parallel Routes and the Traffic Level

This study did not address the merging or demerging of routes. Many airport pairs have routes which pass between the restricted areas considered and some amount of route merging is therefore necessary. This may take place either to the east or west of the hypothetical route structure simulated. The impact of having fewer routes through the restricted areas is that aircraft must be merged earlier in their flight (westbound arrivals) or demerged later in their flight (eastbound departures). During the simulation, conflicts in being as of when the aircraft first entered the simulated area were resolved, but the conflicts were not counted in the results (since resolution would have taken place prior to entering the area). It is possible that some of these conflicts would not have occurred were it not for the route limitations within the simulated area. In this regard, there are two types of such conflicts that are relevant. First, westbound aircraft which enter the simulated area in conflict might not have had a conflict if, a) they were previously on separate routes and, b) the conflict would have been automatically and completely resolved, via their nominal speed differential (if any), by an extra fifty miles of separated routing. Second, eastbound aircraft entering the area in conflict might not have had a conflict if, a) they had requested different enroute routes and, b) the necessary terminal

and transition area routes were available to facilitate demerging prior to the conflict. Conflicts satisfying either of these two conditions are considered sufficiently uncommon that their exclusion from the results should have no noticeable impact.

With regard to the specific geographical area being considered, there is one additional traffic control problem which was not addressed. The simulated area borders on the Los Angeles transition area. Were this a typical transition (and terminal) area, it would be expected that most departing aircraft would have attained their cruise altitude prior to entering the simulated route structure and most arrival aircraft would not have to begin descent until they had traversed the structure. In other words, the simulated area would be used predominantly for enroute (level) flight, which is the environment that this section of the study was designed to address. However, the eastbound departures from LAX include aircraft which are, in general, larger, more heavily loaded, destined for longer flights and at higher altitudes than would be considered average. As a result, some aircraft may still be climbing as they enter the simulated area. To a lesser extent, a similar situation exists for westbound arrivals since the higher flight levels necessitate earlier descents. The transitioning aircraft will cause additional conflicts (primarily of the head-on type) since normal altitude separation will not be in effect.

Other RNAV-related studies have been conducted which include fast time simulations similar to those performed here [2]. These studies, which are discussed in Section 2.5, have shown that the transition-caused conflicts should generally be of primary concern, and this conclusion appears to apply to the Los Angeles area as well. It was not within the scope of this study to address transition areas or transition-induced conflicts. In view of the potential impact of transition conflicts within the geographical region of concern in this section, several comments must be made regarding interpretation of the results. First, the simulated region was assumed to be an enroute area and the simulation results, in both an absolute and relative sense, provide a valid characterization of the impact of route width and/or the number of routes on conflict rates in an enroute environment. The results as applied to the Los Angeles area, however, are considered valid with regard to identifying the relative effect of the number of routes, but may be biased, in absolute terms, as a function of the extent to which transition-induced conflicts occur in the area. The previously conducted studies do not permit accurate quantification of the impact of transition conflicts in this specific region.

As is readily apparent from Figure 2.10, all of the simulations shared one characteristic of particular significance; specifically, very few conflicts occurred. The processing of the projected 1982 traffic tape resulted in determining that the peak hour traffic whose direction was within the bounds shown in Figure 2.9 consisted of fifty flights. This included both eastbound and westbound flights, and all altitude levels. Thus, 200% of the 1982 traffic represents 100 aircraft per hour. From Figure 2.10, if these aircraft are constrained to fly on three routes, only one aircraft in 45 would be expected to enter into a conflict within the area. In an enroute environment, aircraft flying at the same altitude generally have similar cruise speeds. In a structure length of fifty miles, faster aircraft virtually have no opportunity to come into conflict with slower aircraft.

While the hourly conflict rates appeared to have stabilized in the twenty hours of simulation, the types of conflicts which occurred and the resolution techniques employed appeared to be affected significantly by random variation. There were three basic resolution procedures which were used to resolve conflicts -- parallel offsets, altitude reclearances and speed reductions*. With a maximum of twenty-two conflicts occurring in any of the simulations, accurate estimation of the average mix of resolution procedures cannot be expected. In view of the hourly conflict rates observed, it did not appear to be worthwhile to conduct the additional simulations necessary to achieve representative or stable results with regard to the mix of these resolution methods. Aircraft time and fuel penalties and controller workload data are, therefore, not presented. The average aircraft penalties are obviously proportional to the number of conflicts which occur. The number of conflicts were insignificant, and the average aircraft penalties, although random, were equally insignificant.

The average number of conflicts per flight can be obtained from Figure 2.10 by dividing by half the number of flights (since each conflict involves two aircraft). These results are shown in Figure 2.11. While the results show some random variation, the basic characteristics are very apparent. In relative terms, increasing the number of routes markedly reduces the per flight conflict rates. Independent of the traffic level, four routes result in approximately 50% fewer conflicts than three routes. Similarly, four routes can accommodate double the 1982 traffic with the lesser average conflict rate than results from only 120% of the traffic when divided among three routes (i.e., more than a two-thirds increase in traffic can be accommodated with the same level of efficiency by a one-third increase in the number of routes).

With the current navigation accuracies and the route design capabilities inherent with area navigation, three routes can be accommodated between the restricted areas bounding the eastern approach to Los Angeles, and the penalties for the three routes are sufficiently small that a constant ± 4 nm route width in the enroute environment is concluded to be adequate from a capacity viewpoint. This conclusion is based on the use of this area to simulate a worst case enroute situation. The analysis of transition area route width requirements, particularly as epitomized by this unique area was beyond the scope of this study and was not included in the simulation. It is possible that route widths less than ± 4 nm may be required in a few transition areas such as that east of Los Angeles, particularly if increased joint use of restricted airspace, as recommended by the Task Force, does not occur.

*subject to pilot concurrence in accordance with current ATC procedures

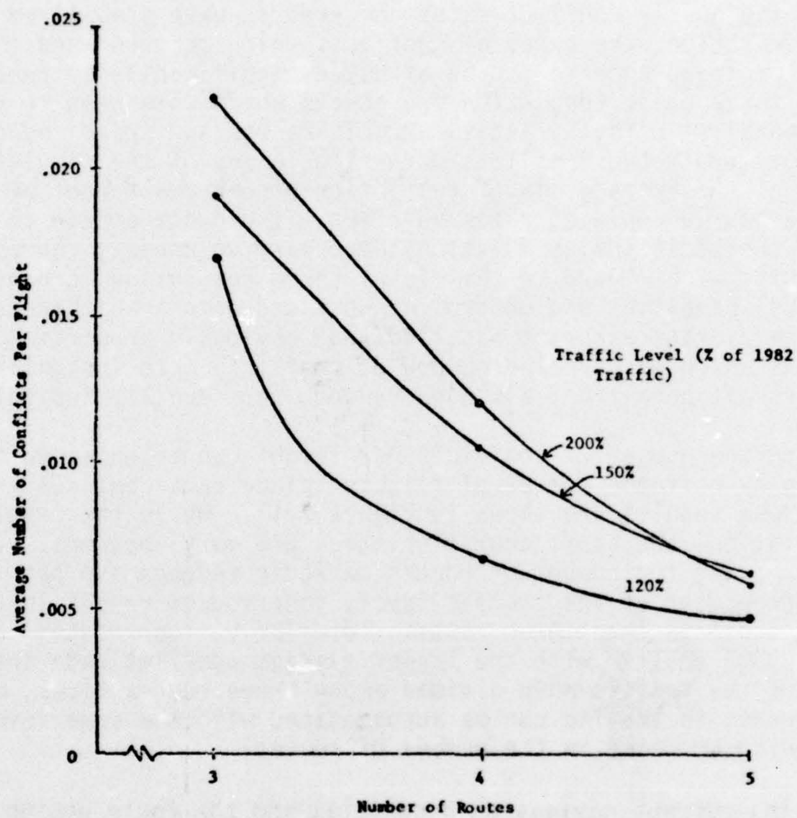


Figure 2.11 Average Number of Conflicts per Flight as a Function of the Number of Parallel Routes and the Traffic Level

2.4 ROUTE LENGTH EFFECTS

Based upon the analysis performed to estimate the economic impact of RNAV [3,5], reduction in route length provides one of the more significant RNAV benefits. Since route width, under hypothetical circumstances, can effect route length by two percent or more, an analysis of this effect was considered important.

To illustrate the effect of route width on route length, a simple geometric relationship can be described. This is shown in Figure 2.12. The route design technique illustrated originates from the "wagon wheel" concept recommended by the RNAV FAA/Industry Task Force [1]. The wagon wheel refers to the circle surrounding the terminal. The enroute or transition route segments join the terminal route segments on this circle. In the strict application of this design concept,

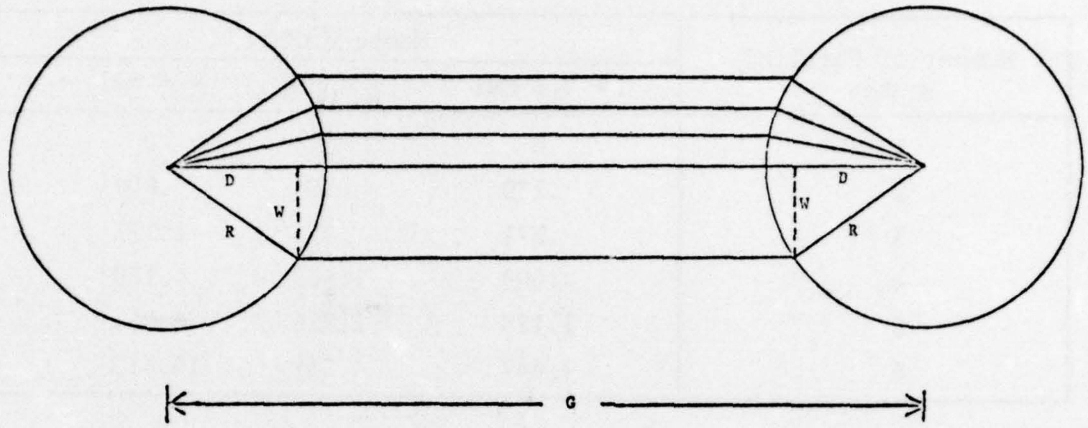


Figure 2.12 Geometric Effect of Route Width on Route Length

the circle is divided into octants, with alternate octants for arrivals and departures. A departure octant would normally encompass the primary runway departure path. The segments external to the circle would be transition segments, on which only one-way traffic would be allowed. The transition segments merge into two-way enroute segments at a distance of 90-120 miles from the terminal.

The route design illustrated in Figure 2.12 is a variation of the wagon wheel concept; its realism, however, becomes apparent later in this chapter. The terminal-to-terminal great circle distance is indicated as G miles. If the enroute segment is removed W miles off the centerline, as if to provide space for additional parallel routes, a mileage penalty of 2(R-D) miles is incurred, where

$$D = \sqrt{R^2 - W^2}$$

Assuming equal traffic distriubtion among the routes and a nominal wagon wheel (terminal area) radius of 45 miles, a table of traffic-weighted average mileage penalties was computed. These are presented in Table 2.2 and are plotted in Figure 2.13. It is apparent from this figure that the impact of route width on route length can, in theory, be very great. For this reason, a more detailed study was undertaken to obtain accurate and realistic estimates of the impact of route width on route length. The current RNAV route design techniques were analyzed and utilized to generate several route structures where route width was the only variable. The resulting route lengths were computed and realistic traffic data was utilized to obtain average flight time and fuel differences among the structures considered.

As in other sections of this report, area selection was the first task. Based upon the 1969 IFR Peak Day Tape and any of the traffic forecasts previously described, the San Francisco-Los Angeles traffic exchange exceeds that of any other airport pair. The second highest exchange is between Los Angeles and Las Vegas, an area which was selected for study in Section 2.3. By considering the other air terminals within the SFO and LAX areas, the total area exchange rate is tripled. A secondary reason for this choice of areas stems from a review of the level 150 airport pair RNAV design, developed at the National Aviation Facilities Experimental Center (NAFEC) [4], illustrated in Figure 2.14.

Number of Parallel Routes	Route Width		
	± 2.5 nmi	± 4 nmi	± 6 nmi
1	0	0	0
2	.139	.356	.804
3	.371	.956	2.173
4	.699	1.808	4.159
5	1.123	2.926	6.851
6	1.647	4.331	10.412

Table 2.2 Average Route Mileage Penalties as a Function of the Number of Parallel Routes (Uniform Traffic Distribution)

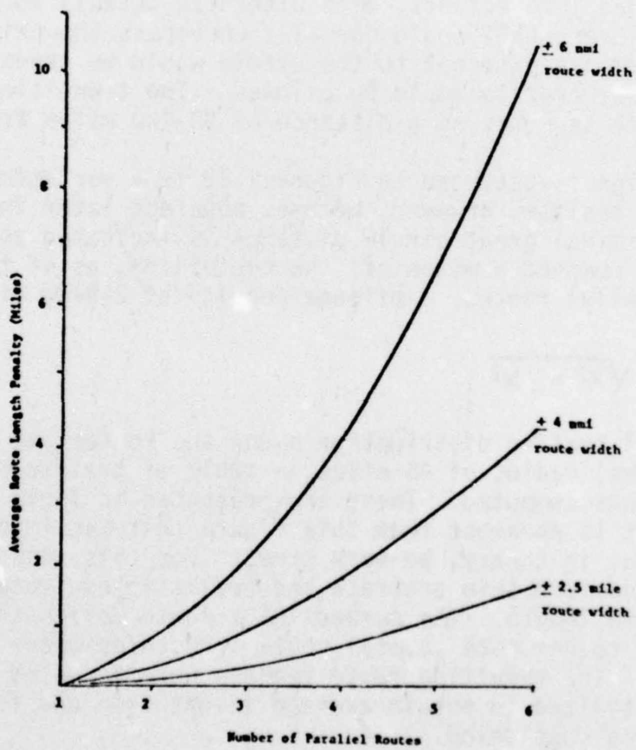


Figure 2.13 Traffic Weighted Average Route Mileage Penalty

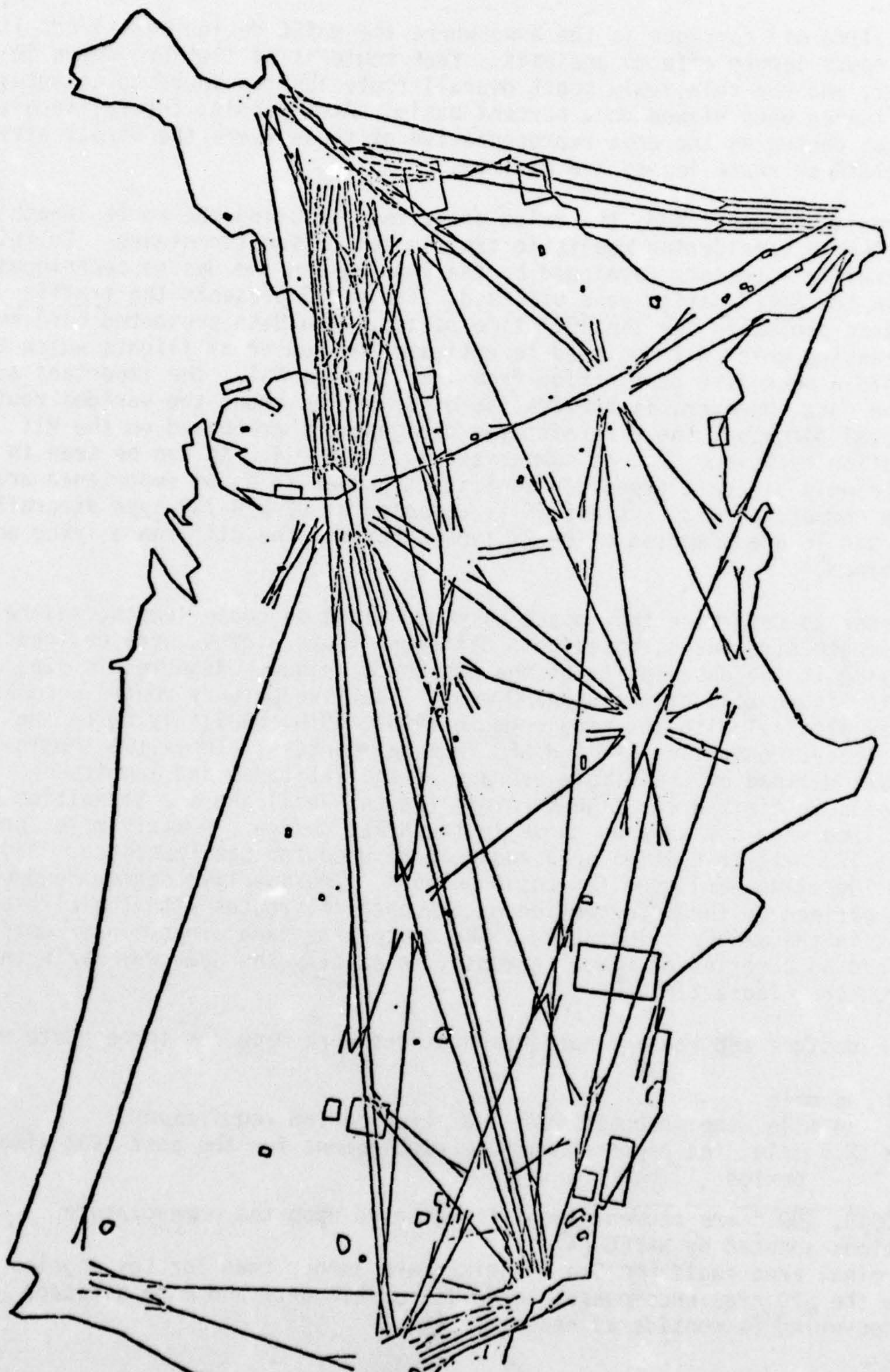


Figure 2.14 NAFEC Level 150 Airport Pair RNAV Route Structure

The California corridor is the area where the NAFEC design best lends itself to a route length effects analysis. Each route is of the form shown in Figure 2.12, and the relatively short overall route lengths serve to accentuate the significance when viewed on a percent basis. As a result, the California corridor was chosen as the area representative of those where the direct effects of route width on route length are maximum.

As previously mentioned, the value of further pursuing the route length analysis lies in considering realistic traffic and design techniques. To this end, the traffic forecasts developed by the FAA [2] and the design techniques inherent in the NAFEC design were utilized. Table 2.3 presents the traffic exchange data projected for the 1977 time period. The data presented here reflect processing which was designed to estimate the number of flights which take place within a peak five hour period from 1 pm to 6 pm PST. The important aspect of the data, however, is the traffic distribution among the various routes, not the total flights. The aircraft type designations are based on the MIT classification technique [2], as summarized in Table 2.4. As can be seen in the tables, the only aircraft types of significant number to be of importance are the medium commercial jets. Class 15 is composed of DC-9/B-737 type aircraft. Classes 9 and 16 are composed of B-727 type aircraft, the difference lying only in performance.

In order to determine the impact of route width on route length, several different route structures, based upon different route widths, were designed. The following is the description of the design technique. A geometric diagram is given in Figure 2.15 of the LAX-SFO area. The five primary routes were assumed to be parallel with the middle route (P001, 0010, C001)* lying on the great circle arc connecting LAX and SFO terminal centers. These two terminal centers were defined by the simple average of the latitudes and longitudes of the terminals in their area. The terminal (wagon wheel) and the transition area radii utilized were the same as those in the NAFEC design. A sixty mile terminal area and a 120 mile transition area radius were used for San Francisco. Radii of 45 and 100 miles were used for Los Angeles**. The specific segment endpoints were then defined as the intersection of the parallel routes with the circle boundaries in the manner illustrated. The routes for each airport pair were then defined as a series of route segments, in exactly the same way as in the NAFEC structure (Table 2.5).

Route designs and route length computations were made for three route widths.

- ±6 mile
- ±4 mile, the proposed 1977-1982 time period requirements
- ±2.5 mile, the proposed enroute requirement for the post-1982 time period [1].

*"P001, 0010, C001" are segment identifiers based upon the nomenclature conventions adopted by NAFEC [4].

**The terminal area radii for San Francisco are larger than for Los Angeles because the SFO area encompasses three larger airports and more airspace for maneuvering is considered necessary [4].

Table 2.3 Projected 1977 Traffic Exchange Data for the California Corridor (Number of Flights, or Fraction Thereof, in the Period From 1 to 6 PM PST)

GENERAL CATEGORY	EXECUTIVE JET			MEDIUM COMMERCIAL JET			STANDARD COMMERCIAL JET			HEAVY COMMERCIAL JET			TOTAL
SUB-CATEGORY	A	B	C	A	B	C	A	B	C	A	B	C	
CATEGORY NUMBER	8	13	14	9	15	16	10	17	18	11	19	20	
AIRPORT PAIR													
BUR-OAK				2.0	1.0	1.0							4.0
BUR-SFO				3.0	1.3	4.7							9.0
BUR-SJC				3.1	3.3	3.0							9.4
LAX-OAK				3.0	2.2	8.7							13.9
LAX-SFO	.2			3.2	5.6	13.1	4.0	1.2	2.0	1.0		4.0	34.3
LAX-SJC	1.0			3.2	6.0	5.0							15.2
OAK-ONT				1.0		1.0							2.0
ONT-SFO				3.7	1.0	5.8							10.5
ONT-SJC				3.0		1.8							4.8
SFO-SNA				4.7	2.0	1.0							7.7
SJC-SNA				1.0	2.0	2.5							5.5
TOTAL	1.2			30.9	24.4	47.6	4.0	1.2	2.0	1.0		4.0	116.3

Table 2.4 Enroute Aircraft Performance Categories

AIRCRAFT TYPE		WEIGHT RANGE (lb)
8	Business Jet, Standard Performance	6,500-60,000
9	Light Transport, Standard Performance	60,000-155,000
10	Standard Transport, Standard Performance	155,000-300,000
11	Heavy Transport, Standard Performance	>300,000
13	Business Jet, Low Performance	6,500-60,000
14	Business Jet, High Performance	6,500-60,000
15	Light Transport, Low Performance	60,000-155,000
16	Light Transport, High Performance	60,000-155,000
17	Standard Transport, Low Performance	155,000-300,000
18	Standard Transport, High Performance	155,000-300,000
19	Heavy Transport, Low Performance	>300,000
20	Heavy Transport, High Performance	>300,000

Table 2.5 California Corridor Airport Pair/Route Definition

Route Identifier	% of Traffic Using Route	Route Segment I.D.'s			
1. BUROAKR1	100	Q001	001A	D001	
2. BURSFOR1	100	Q001	001A	D001	
3. BURSJCR1	100	S001	001B	F001	
4. LAXOAKR1	100	Q001	001A	D001	
5. LAXSFOR1	75	Q001	001A	D001	
6. LAXSFOR2	25	R001	048A	C048	
7. LAXSJCR1	100	S001	001B	F001	
8. OAKBURR1	100	P001	0010	C001	
9. OAKLAXR1	100	P001	0010	C001	
10. OAKONTR1	100	P104	104A	D104	
11. ONTOAKR1	100	R104	Q024	104A	C104
12. ONTSFOR1	100	R104	Q024	104A	C104
13. ONTSJCR1	100	R104	Q024	104A	C104
14. SFOBURR1	100	P001	0010	C001	
15. SFOLAXR1	75	P001	0010	C001	
16. SFOLAXR2	25	P048	048A	E001	
17. SFOONTR1	100	P104	104A	D104	
18. SFOSNAR1	100	P001	0010	C001	
19. SJCBURR1	100	T001	001B	G001	
20. SJCLAXR1	100	T001	001B	G001	
21. SJCONTR1	100	P104	104A	D104	
22. SJCSNAR1	100	T001	001B	G001	
23. SNASFOR1	100	Q001	001A	D001	
24. SNASJCR1	100	S001	001B	F001	

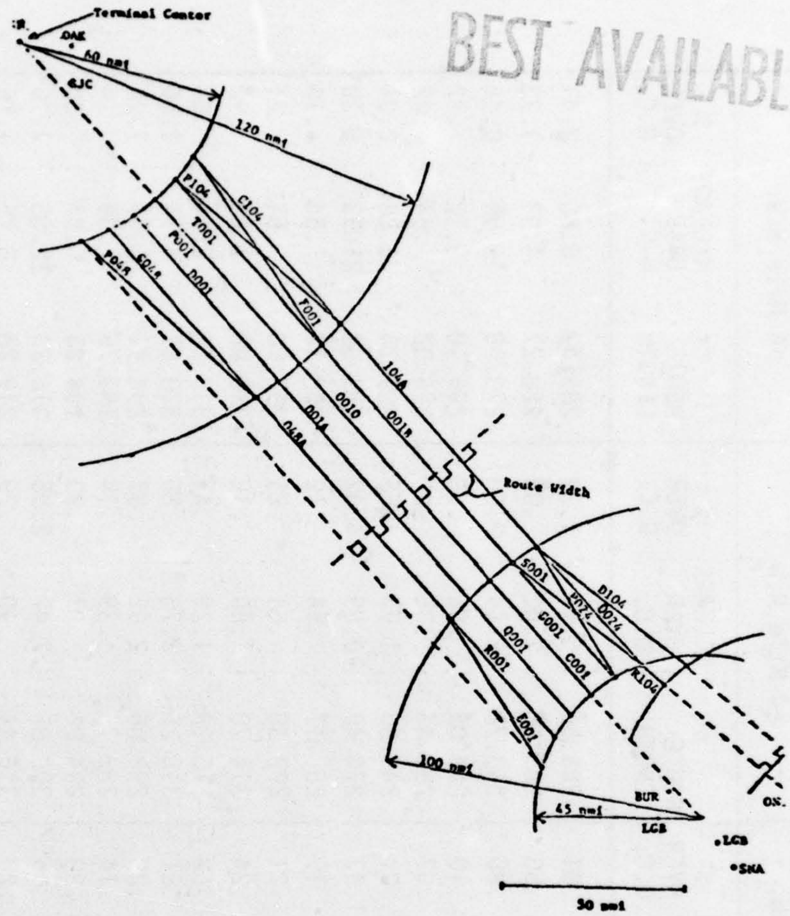


Figure 2.15 Analytical Design for the SFO-LAX Routes

To ensure the suitability of the analytical technique when applied to varying route widths, each design was plotted (Figures 2.16, 2.17 and 2.18). Each structure appears reasonable for its respective route width. The route length results are given in Table 2.6.

Table 2.7 presents the traffic flow on each route. These data are based upon the traffic exchange data in Table 2.3. The data in Table 2.3 were divided in half to approximate the one-way traffic rates. The flights were then assigned to the routes based upon Table 2.5. The purpose of this effort was to determine estimates of the relative number of aircraft of each type which would be expected to traverse each route. Table 2.8 presents the total flight mile results obtained by summing, for each route, the product of the number of flights and the route length. Dividing the total flight mile data by the total number of flights yielded the average per flight route length penalties which are plotted in Figure 2.19.

Table 2.6 Route Length Results for California Corridor

ROUTE I.D.	GREAT CIRCLE DIST.	±2.5 Mile R.W.			±4 Mile R.W.			±6 Mile R.W.		
		ROUTE LENGTH	MILEAGE OVER G.C.	% OVER G.C.	ROUTE LENGTH	MILEAGE OVER G.C.	% OVER G.C.	ROUTE LENGTH	MILEAGE OVER G.C.	% OVER G.C.
BUR OAK R1	282.63	284.92	2.29	.81	286.56	3.93	1.39	289.43	6.80	2.41
BUR SFO R1	283.36	284.78	1.42	.50	285.98	2.62	.93	288.27	4.91	1.73
BUR SJC R1	257.34	259.39	2.05	.80	263.78	6.44	2.50	273.93	16.59	6.45
LAX OAK R1	293.06	293.59	.53	.18	294.02	.96	.33	295.18	2.12	.72
LAX SFO R1	293.38	293.45	.06	.02	293.44	.06	.02	294.02	.64	.22
LAX SFO R2	293.38	293.65	.26	.09	245.30	1.92	.65	300.24	6.86	2.34
LAX SJC R1	267.59	272.86	5.28	1.97	278.48	10.89	4.07	289.52	21.93	8.20
OAK BUR R1	282.63	283.17	.54	.19	283.17	.54	.19	283.17	.54	.19
OAK LAX R1	293.06	293.68	.61	.21	293.68	.61	.21	293.68	.61	.21
OAK ONT R1	314.10	314.86	.76	.24	314.70	.60	.19	316.98	2.88	.92
ONT OAK R1	314.10	316.06	1.96	.62	315.38	1.28	.41	316.24	2.14	.68
ONT SFO R1	315.53	318.08	2.54	.81	318.26	2.73	.86	320.27	4.74	1.50
ONT SJC R1	289.24	291.65	2.41	.83	292.06	2.82	.97	294.91	5.67	1.96
SFO BUR R1	283.36	283.75	.39	.14	283.75	.39	.14	283.75	.39	.14
SFO LAX R1	293.38	294.26	.87	.30	294.26	.87	.30	294.26	.87	.30
SFO LAX R2	293.38	295.29	1.90	.65	300.86	7.47	2.55	316.23	22.85	7.79
SFO ONT R1	315.53	316.16	.63	.20	316.44	.90	.29	319.28	3.75	1.19
SFO SNA R1	323.16	323.30	.15	.05	323.30	.15	.05	323.30	.15	.05
SJC BUR R1	257.34	257.57	.23	.09	258.22	.88	.34	259.95	2.61	1.01
SJC LAX R1	267.59	269.70	2.11	.79	271.19	3.60	1.35	273.88	6.30	2.35
SJC ONT R1	289.24	289.80	.56	.19	290.01	.77	.27	292.90	3.65	1.26
SJC SNA R1	297.18	297.47	.29	.10	298.07	.89	.30	299.43	2.25	.76
SNA SFO R1	323.16	323.51	.35	.11	323.98	.83	.26	326.04	1.89	.58
SNA SJC R1	297.18	299.10	1.92	.65	302.60	3.32	1.79	309.84	12.66	4.26

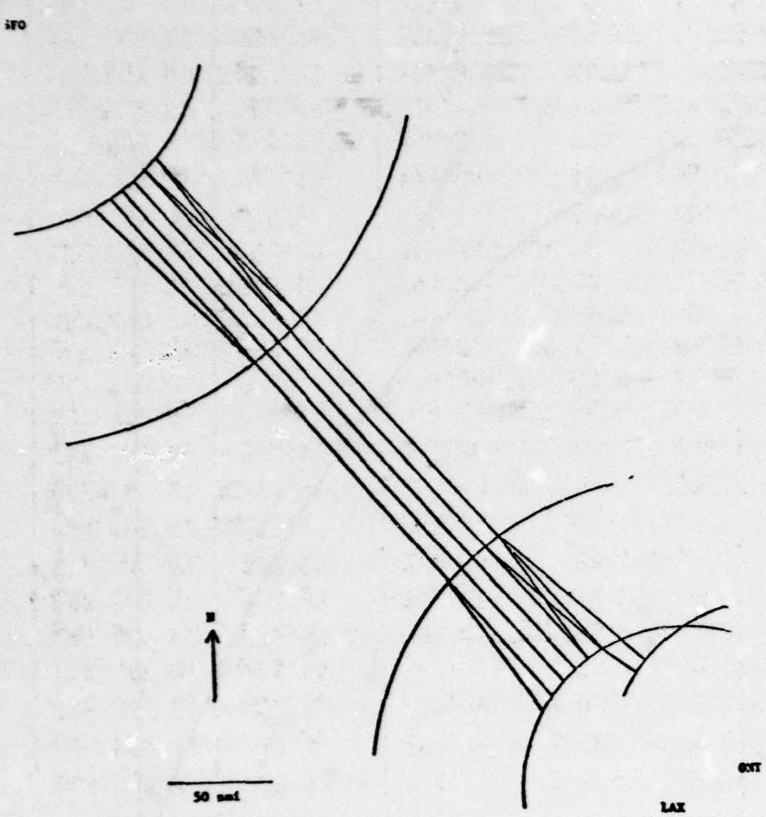


Figure 2.16 Analytical Design for the California Corridor (±2.5 nm Route Width)

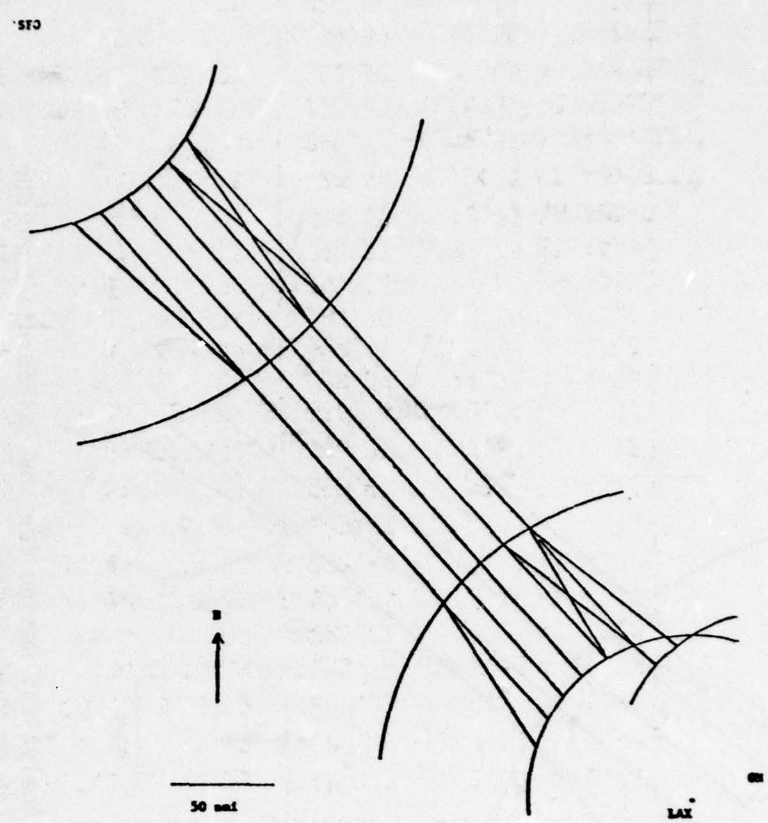


Figure 2.17 Analytical Design for the California Corridor (±4 nm Route Width)

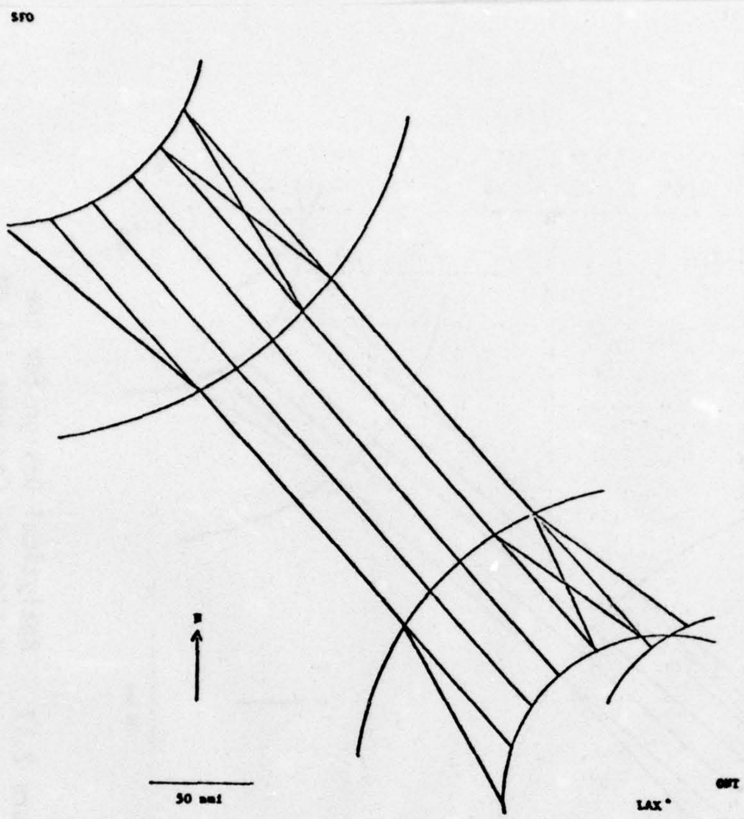


Figure 2.18 Analytical Design for the California Corridor (±6 nm Route Width)

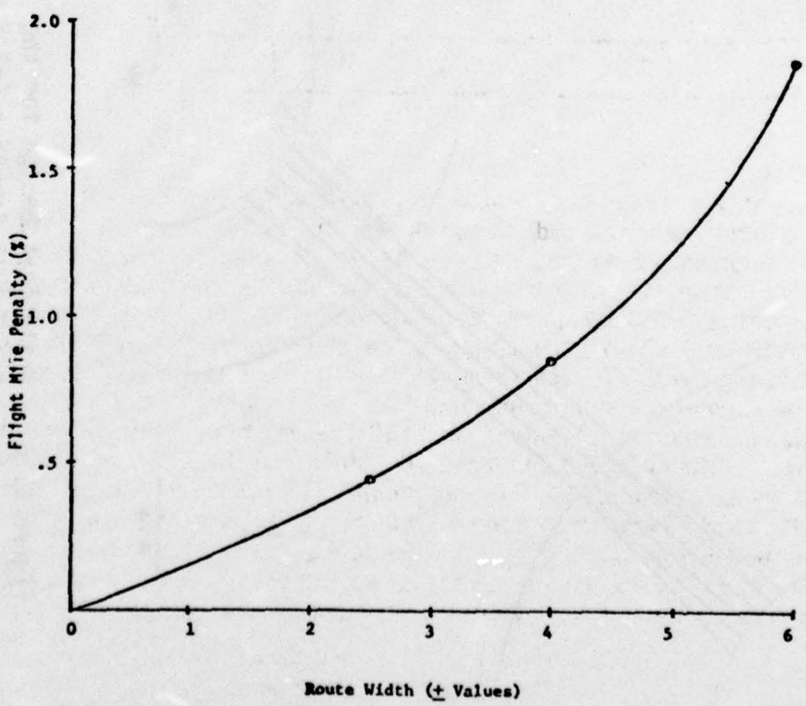


Figure 2.19 Traffic Weighted Average Flight Mile Percent Penalty (SFO-LAX Corridor)

Table 2.7

Number of Flights in the Period 1-6 PM PST
Assigned to Each Route (Projected 1977 Data)

Route I.D.		Aircraft Type			Total
		9	15	16	
1.	BUROAKR1	1.0	.5	.5	2.0
2.	BURSFOR1	1.5	.7	2.3	4.5
3.	BURSJCR1	1.6	1.6	1.5	4.7
4.	LAXOAKR1	1.5	1.1	4.3	6.9
5.	LAXSFOR1	1.2	2.1	4.9	8.2
6.	LAXSFOR2	.4	.7	1.6	2.7
7.	LAXSJCR1	1.6	3.0	2.5	7.1
8.	OAKBURR1	1.0	.5	.5	2.0
9.	OAKLAXR1	1.5	1.1	4.4	7.0
10.	OAKONTR1	.5		.5	1.0
11.	ONTOAKR1	.5		.5	1.0
12.	ONTSFOR1	1.8	.5	2.9	5.2
13.	ONTSJCR1	1.5		.9	2.4
14.	SFOBURR1	1.5	.6	2.4	4.5
15.	SFOLAXR1	1.2	2.1	5.0	8.3
16.	SFOLAXR2	.4	.7	1.6	2.7
17.	SFOONTR1	1.9	.5	2.9	5.3
18.	SFOSNAR1	2.4	1.0	.5	3.9
19.	SJCBURR1	1.5	1.7	1.5	4.7
20.	SJCLAXR1	1.6	3.0	2.5	7.1
21.	SJCONTR1	1.5		.9	2.4
22.	SJCSNAR1	.5	1.0	1.3	2.8
23.	SNASFOR1	2.3	1.0	.5	3.8
24.	SNASJCR1	.5	1.0	1.2	2.7
	TOTAL	30.9	24.4	47.6	102.9

Independent of where the route length penalty is actually incurred, the additional mileage was assumed to be flown in cruise mode, and the time and fuel penalties computed accordingly. A DC-9 aircraft flying on these routes would normally request a cruise altitude of 31,000 or 33,000 ft, depending upon the direction of travel. A true airspeed of 450 knots and a per mile fuel consumption of 12.47 pounds would be considered nominal at these altitudes. Similarly, a B-727 would request an altitude of 29,000 or 31,000 ft, with a true airspeed of 470 knots and fuel consumption of 16.78 lbs per mile. With these data, the route length penalties were transformed into time and fuel penalties. These are tabulated in Table 2.9 and plotted in Figure 2.20. While the largest route width imposes penalties which might be viewed as significant, the comparison of primary concern is between ±4 and ±2.5 mile route widths. The weighted average (by route and aircraft type, from Tables 2-7 and 2-9) user penalty increases associated with a ±4 mile route width, as compared to a ±2.5 mile route width, are summarized below:

Mileage:	1.176
Time (min):	0.153
Fuel (lbs):	17.86

Table 2.8 California Corridor:

Total Flight Miles During the Period 1-6 PM PST (Projected 1977 Traffic)

Route Width (nm)	Aircraft Type 9	15	16	TOTAL	Average Route Length
0 (Great Circle)	9052.69	6949.63	13848.21	29850.53	290.104
±2.5	9091.25	6987.16	13905.11	29983.52	291.385
±4.0	9122.04	7028.49	13953.95	30104.48	292.560
±6.0	9205.69	7120.79	14085.03	30411.51	295.544

Effect of Route Width on Average Route Length:

Route Length Percent Increase Associated With Route Width (A) Relative to Route Width (B)

Route Width A \ B	0 (Great Circle)	±2.5 nm	±4.0 nm
±2.5 nm	.442		
±4.0 nm	.847	.405	
±6.0 nm	1.875	1.434	1.029

Table 2.9 California Corridor Average Per Flight Time and Fuel Penalties

Average Per Flight Penalties Relative to the Great Circle

Route Width	DC-9 Mileage (nmi)	DC-9 Time (min.)	DC-9 Fuel (lbs.)	B-727 Mileage (nmi)	B-727 Time (min.)	B-727 Fuel (lbs.)
± 2.5	1.538	.205	19.18	1.216	.155	20.40
± 4.0	3.232	.431	40.30	2.231	.285	37.44
± 6.0	7.015	.935	87.48	4.966	.634	83.33

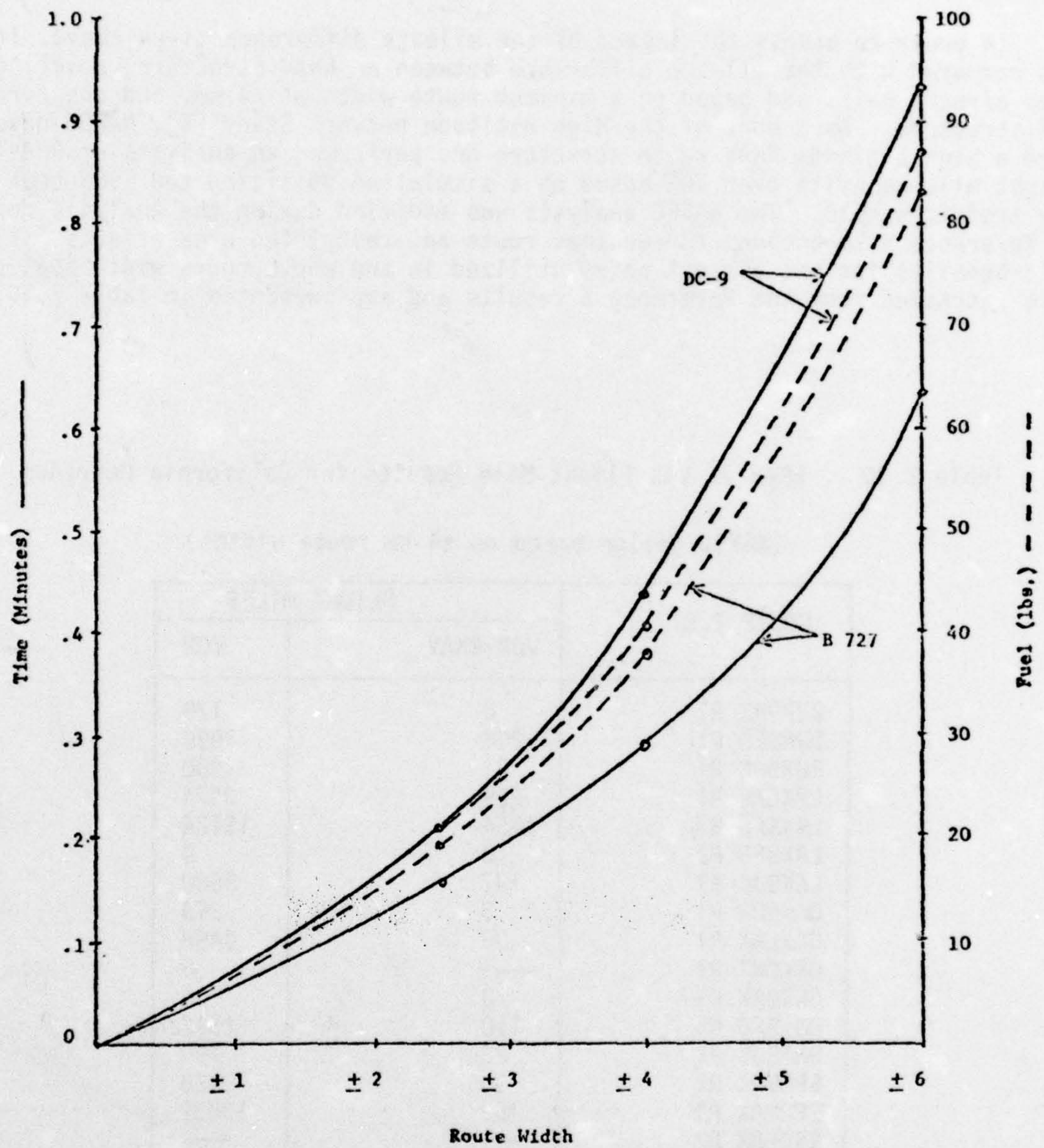


Figure 2.20 California Corridor Average Per Flight Time and Fuel Penalties Due to Route Width

The mileage penalty is noticeably less than the 1.803 miles which would be predicted by the geometric model presented earlier. While the transition area design may account for some of this difference, the primary factor is the traffic-to-route assignments. While some of the routes have significant penalties (5.61 mile difference between ±2.5 and ±4 mile route widths for LAXSJC R1), most of the traffic utilizes the more efficient routes. This is strictly intentional in that the more efficient routes were designed for the airport pairs of higher exchange.

In order to assess the impact of the mileage difference given above, it was compared with the mileage difference between an RNAV structure, covering the same airport pairs and based on a minimum route width of ±4 nm, and the current VOR structure. As a part of the High Altitude Network Study [4], NAFEC developed a high altitude RNAV route structure and performed an analysis of RNAV flight mile benefits over VOR based on a simulation utilizing the 1969 Peak Day traffic sample. The NAFEC analysis was modified during the analysis reported in Reference 5 to account for weather route and restricted area effects. Flight mile benefits for the airport pairs utilized in the above route width analysis were extracted from the Reference 5 results and are presented in Table 2.10.

Table 2.10 RNAV vs VOR Flight Mile Results for California Corridor

(NAFEC design based on ±4 nm route widths)

ROUTE I.D.	FLIGHT MILES	
	VOR-RNAV	VOR
BUROAK R1	0	179
BURSFO R1	208	1990
BURSJC R1	81	1900
LAXOAK R1	269	3474
LAXSFO R1	1454	15124
LAXSFO R2	0	0
LAXSJC R1	137	2688
OAKBUR R1	3	364
OAKLAX R1	33	3458
OAKONT R1	—	0
ONTOAK R1	0	0
ONTSFO R1	110	1592
ONTSJC R1	22	950
SFOBUR R1	30	1820
SFOLAX R1	163	13832
SFOLAX R2	—	—
SFOONT R1	22	1496
SFOSNA R1	-14	1456
SJCBUR R1	-2	1980
SJCLAX R1	17	2520
SJCONT R1	5	925
SJCSNA R1	-32	1440
SNASFO R1	114	1782
SNASJC R1	48	1536
TOTAL	2668	60506

RNAV benefit over VOR = $\frac{2668}{60506}$ = 4.41%

The average flight length for the ±4 nm route width routes in the route width analysis is 292.56 miles. In order to compare these routes with the NAFEC route structure it is necessary to subtract 45 miles for each terminal area since this was the procedure used in the NAFEC study to define the enroute portion of the distance between airport pairs. The average flight length on this basis is then 202.56 miles, and the average mileage penalty of 1.176 miles, for a ±4.0 mile route width compared with a ±2.5 mile route width, represents 0.58% of the ±4 mile route width flight miles. As shown in Table 2.10, the flight mile benefit derived from an RNAV structure with ±4 nm route widths is 4.41% of the VOR flight miles, or

$$\frac{V-R_4}{V} = .0441 \qquad (1)$$

and

$$\frac{R_4-R_{2.5}}{R_4} = .0058 \qquad (2)$$

where V = VOR flight miles

R_4 = ±4 nm route width RNAV flight miles

$R_{2.5}$ = ±2.5 nm route width RNAV flight miles

By combining equations (1) and (2), it can be seen that the flight mile benefit of a ±2.5 nm route width RNAV structure compared with the VOR structure would be 4.96% of the VOR flight miles.

The additional RNAV route length benefits realized by ±2.5 nm route width's compared with ±4.0 nm route widths is then only .55%. It is therefore concluded based on this analysis, that RNAV route widths of ±4 nm are satisfactory from the viewpoint of route length savings, and that there is no requirement for a reduction of route widths to ±2.5 nm as recommended by the Task Force.

2.5 ADDITIONAL ENROUTE ROUTE WIDTH VALIDATION

The analysis presented thus far in this section has been based on selected high density areas. As stated in Section 3.2.1, the use of any "designed" structure would have led to results influenced by the peculiarities of the design, and would therefore have detracted from the general applicability of the study results. However, since the results of the analysis of the selected high density areas indicate that enroute route width of ±4 nm are adequate to support post-1982 traffic demand in an efficient manner, it was considered appropriate to review the results of previous simulations and analyses which were based on a uniquely designed RNAV structure, utilizing route widths of ±4 nm, to determine if further validation of the results of this study was apparent in the previous study.

The National Aviation Facilities Experimental Center (NAFEC) of the Federal Aviation Administration conducted a study [4] in which enroute RNAV route structures were developed to evaluate the RNAV Task Force concepts for the application of area navigation in the enroute high altitude airspace and to provide data for system and user payoff analyses. An evolutionary approach was applied to the route structure development, with the designs progressing from a nominal 50 airport pair structure to a nominal 150 airport pair structure and finally to a nominal 250 airport pair structure. The actual number of airport pairs exceeded

the nominal since additional airport pairs were added if the addition could be made without impacting the basic structure for that level. The level 250 structure actually contained 429 airport pairs. All the structures were based on a minimum route width of ±4 nm, and it was not found necessary to reduce route width below this value in order to produce designs which were considered to be efficient on a judgemental basis.

The efficiency of the resulting designs was then analyzed from two viewpoints: route length and capacity [4]. A flight mile weighted average route length savings of approximately 2% was calculated, based on 1969 peak day traffic data adjusted to represent 1977 traffic projections. The designs were then subjected to fast time simulations using the same traffic samples and an estimate of the capacity of the designs was made in terms of conflict count. It was found that an increase in traffic from present day levels to projected 1982 levels of 31.4% resulted in an increase in conflicts of 57.8% on the present high altitude structure. The corresponding increase in conflicts on the RNAV structure, compared with today's traffic on the present VOR structure was only 17.6%. Although no attempt was made to quantify an "acceptable" conflict level, this nominal increase in conflicts over the current level tends to validate the efficiency of the RNAV design based on a ±4 nm route width.

In this section, enroute route width requirements have been analyzed from the viewpoints of route length impact, route design efficiency, and airspace capacity, with the results supporting the conclusion that constant enroute route widths of ±4 nm, as recommended by the RNAV Task Force for the 1977 period, are adequate for the post-1982 period, and that further route width reduction is not necessary. The utilization of constant route widths, as opposed to the currently employed splayed routes, are required for the necessary design efficiency and to maximize the use of non-radar procedural separation through parallel offsets.

3.0 TERMINAL AREA ROUTE WIDTH REQUIREMENTS

Terminal area arrival capacity can be defined as the ability of the system to accommodate the necessary simultaneous approach paths and to deliver aircraft to the final approach fixes with minimum delay. Similarly, departure capacity can be defined as the ability of the system to accommodate the necessary simultaneous departure paths with a minimum of delay. Total capacity may then be defined in terms of establishing the optimum simultaneous mix of arrival and departure capacities.

Terminal area capacity is affected by a great many factors, such as those listed below:

- availability of maneuvering airspace to achieve optimum sequencing
- availability of airspace to accommodate an efficient terminal area design to meet anticipated traffic demand
- runway acceptance rates
- longitudinal spacing accuracy
- achievable range of arrival, approach, and departure ground speeds
- achievable time control accuracies
- achievable final approach lateral separation accuracy
- ATC procedures
- controller workload
- pilot workload
- aircraft performance characteristics
- other constraints (weather, noise abatement, etc.)
- achievable procedural separation

The proposed utilization of Area Navigation in the terminal area is predicated on maximizing the use of procedurally separated routes with a minimum requirement for controller intervention. The issue to be addressed in this section is to analyze the impact of route width on terminal area capacity in order to determine if the current route width requirements of ±2 nm or ±4 nm, depending upon orientation and distance from the VORTAC, as described in AC 90-45A [9], are adequate for the future RNAV environment, or if they must be reduced as recommended by the RNAV Task Force to ±1.5 nm.

The factors affecting terminal area capacity which may be expected to exhibit the greatest dependence on route width are the first two in the above list. In a related study [6] RNAV designs were created for seven major terminal areas. These designs initially were based on a ±1.5 nm route width for the post-1982 time period, as recommended by the Task Force. The designs were optimized through an iterative design/analysis procedure, based on both user economic and ATC impact considerations. In the course of this procedure, it was determined that terminal area route widths as currently required by AC 90-45A could be utilized with a negligible impact on user economics and the ATC system. Significant time and fuel savings were evident in the all-RNAV post-1982 design as compared with current VOR/radar vector routes [5], and the results of real time simulations of the New York terminal area [7,8] indicated a significant reduction in controller workload and an increase in arrival operation rates.

The results of the economic analyses and the real time simulations tend to confirm the overall efficiency of terminal area RNAV designs utilizing the route widths currently required. The remainder of this section presents an analysis of the availability of maneuvering airspace required for sequencing in high density terminal areas with currently required route widths.

3.1 TERMINAL AREA ROUTE WIDTH REQUIREMENTS METHODOLOGY

The approach utilized in the analysis was to develop a model relating delay maneuvering geometry to sequencing distance requirements and to analyze specific terminal area designs for availability of the required airspace. The New York and Miami terminal areas were chosen for this study. The choice of New York was considered appropriate in view of the fact that three major airports exist in this area, and the severity of the maneuvering airspace requirement can be expected to equal or exceed that of any other. The New York terminal area design was based on constant ±2 nm route widths throughout, which are supported by VORTACs at the periphery of the terminal area where required. Miami was chosen as an example of a terminal area which is supported by only two VORTACs, both near the center of the terminal area, and whose routes are either ±2 nm or ±4 nm in width, according to the requirements of AC 90-45A [9]. The post-1982 RNAV designs for the New York terminal area NE and SW flow configurations are shown in Figures 3.1 and 3.2 and the Miami terminal area east flow configuration is shown in Figure 3.3.

The airspace required for departure sequencing is considered to be nominal. The departure times can be fairly accurately controlled and departure routes are procedurally separated except in a few cases where they are merged prior to reaching the high altitude departure waypoint. In these cases a natural altitude separation will usually exist because of the difference in path length from the runway to the merge point. Consequently, it was considered adequate to provide only single passing route areas for departure routes in the New York terminal area.

A basic characteristic of the terminal area design is the provision for path shortening, or "corner cutting", by arriving aircraft. The primary concern here is to provide adequate airspace for path stretching maneuvers. For arrivals, terminal area route widths must support a converging capacity requirement where the goal is to accommodate arriving aircraft in a queue which will result in minimum allowable in-trail spacing at the final approach fixes. The approach used in analyzing the availability of airspace in which to adjust interarrival distance was as follows:

(1) establish a set of "worst case" early arrival assumptions
(2) determine path stretching requirements for each route segment, based on the assumptions
(3) define a model relating delay fan geometry to sequencing distance requirements
(4) define delay areas for each route segment by plotting polygons in which the delay fan can be inscribed with a ±2 nm route width without violating procedural separation from routes/airspace under other controllers' jurisdiction
(5) determine if available path stretching capability meets or exceeds required capability

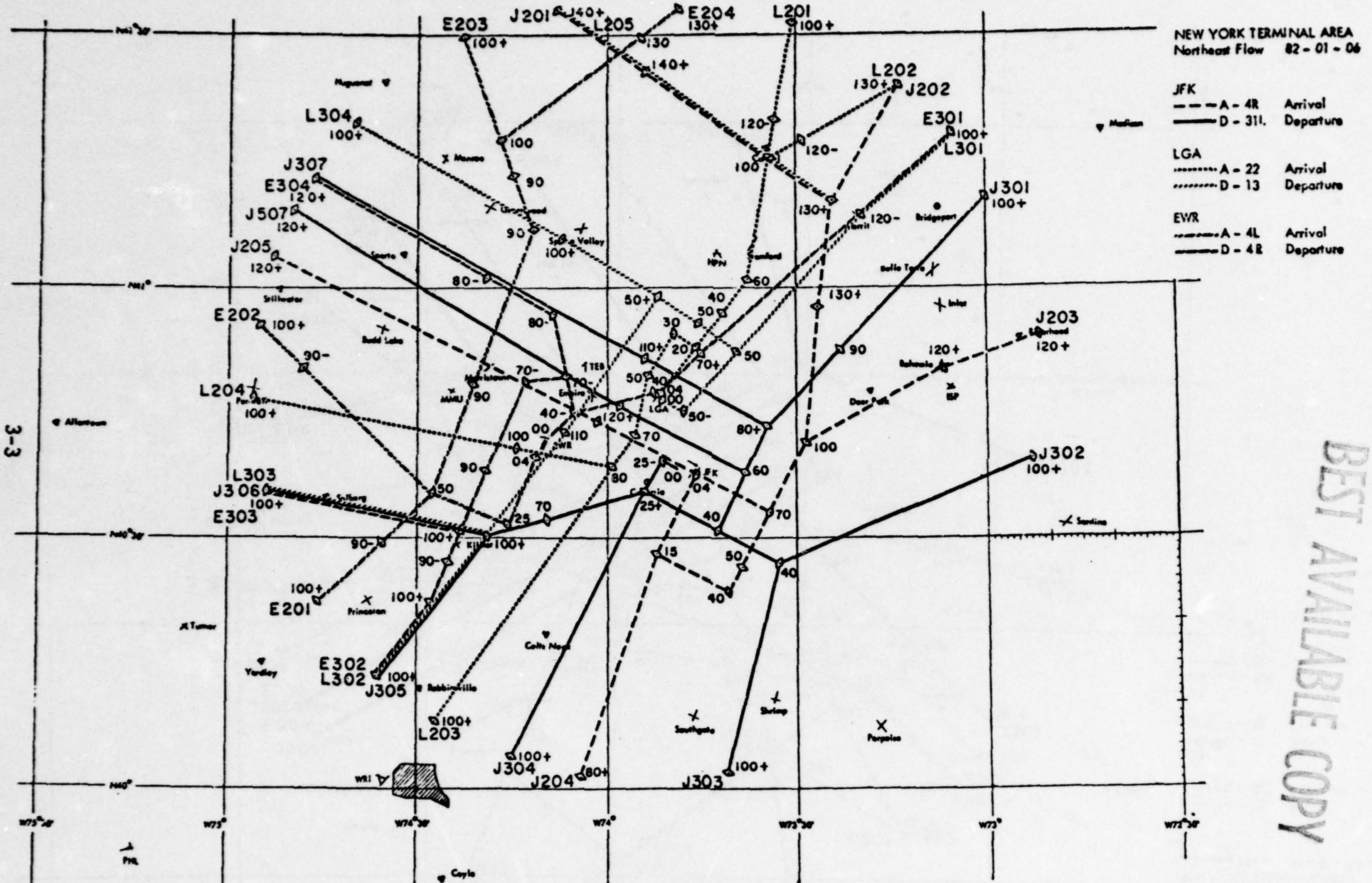


Figure 3.1 New York Terminal Area - 1982 RNAV Routes - Northeast Flow

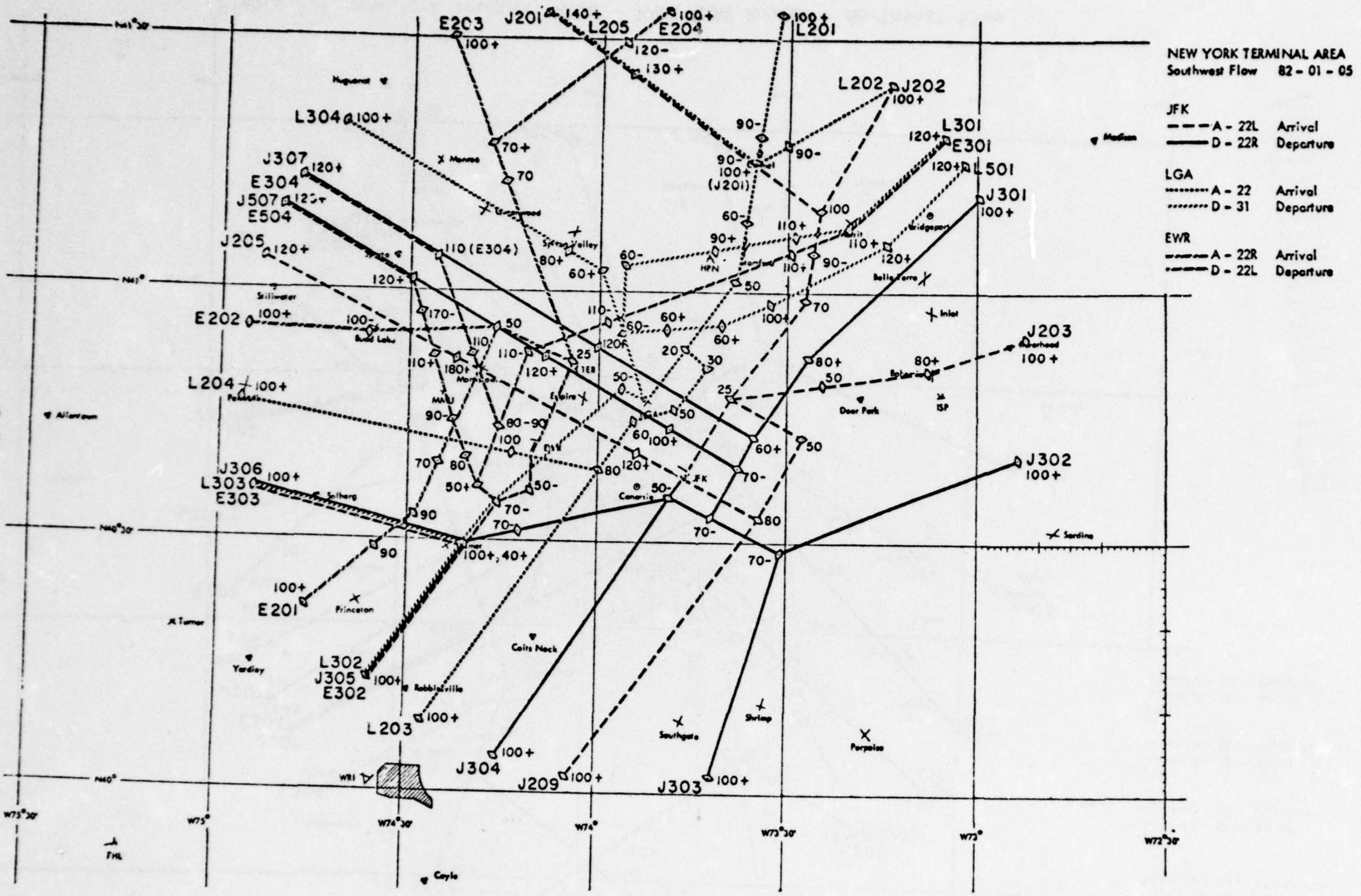


Figure 3.2 New York Terminal Area - 1982 RNAV Routes - Southwest Flow

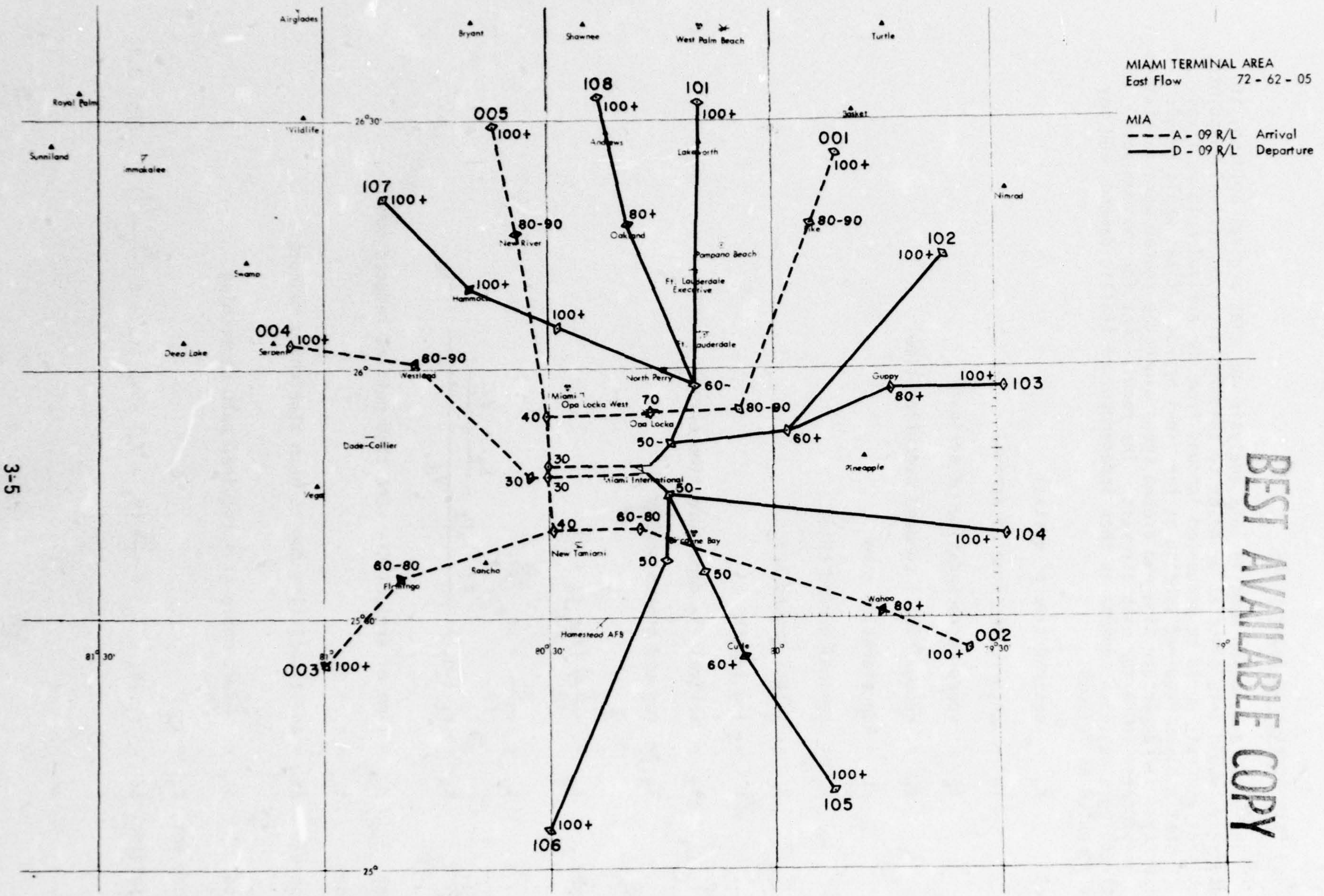


Figure 3.3 Miami Terminal Area - 1982 RNAV Routes - East Flow

3.1.1 Path Stretching Assumptions

The basic assumption made in this analysis was that arrival holding, if necessary, would take place at or prior to the high altitude arrival waypoints, and that aircraft would be sequenced inbound from the arrival holding fixes such that minimum required spacing at the final approach fixes would result if arrival fix departure time and ground speed along the routes were maintained at an expected value for each aircraft. The requirement for maximum path stretching along each segment is then independent of traffic demand, and may be computed as follows:

let t_d = desired time of arrival

t_u = uncorrected time of arrival

t_s = speed corrected time of arrival

r_t = recognition + command execution time

d_t = deceleration time

V_n = nominal ground speed

V_a = actual ground speed

ℓ = leg length

Δt_a = arrival fix departure time error

V_d = reduced ground speed

then
$$t_d = \frac{\ell}{V_n} \text{ (for } t_0 = 0)$$

$$t_u = \frac{\ell}{V_a} + \Delta t_a$$

$$t_s = r_t + d_t + \frac{\ell - V_a r_t - \frac{V_a + V_d}{2} d_t}{V_d} + \Delta t_a$$

let t_{ps} = time of arrival via stretched path at reduced speed

then $t_{ps} = t_s + \Delta t_p$

where Δt_p = additional time due to path stretching maneuver

and, $\Delta t_p = \frac{\Delta \ell}{V_d}$, where $\Delta \ell$ = required path stretching

then set, $t_{ps} = t_d$

yielding
$$\Delta \ell = r_t (V_a - V_d) + \frac{d_t}{2} (V_a - V_d) - V_d \Delta t_a - \ell \left(\frac{V_n - V_d}{V_n}\right) \quad \text{(Eq. 3.1)}$$

The following assumptions were made to approximate worst case conditions for the parameters in Equation 3.1:

assumptions (worst case conditions):

(1) arriving aircraft depart holding pattern such that arrivals at high altitude arrival fix are 2 minutes early (Δt_a = -2 min.)

(2) arrivals at arrival route merging points are 1 minute early (Δt_a = -1 min.)

(3) indicated airspeed is 250 knots within the terminal area, except below the lateral limits of the TCA where it is 200 knots

(4) sea level temperature is 38°C with a standard lapse rate

(5) nominal ground speed (V_n) is based on TAS + 20 knots

(6) actual ground speed (V_a) is TAS + 40 knots

(7) reduced ground speed (V_d) is based on 200 knots IAS + 40 knot tailwind

(8) recognition and command execution time (r_t) is based on time to travel 3 miles plus 30 seconds for arrival fixes and on time to travel 2 miles plus 15 seconds for intermediate fixes

(9) minimum IAS is 200 knots, and deceleration time (d_t) is based on 25 knots per minute IAS

(10) bank angle is limited to 25 degrees

Based on these assumptions, the maximum path stretching requirement for each arrival route was computed. Results are summarized in Table 3.1 for the New York SW flow, Table 3.2 for the New York NE flow, and Table 3.3 for the Miami east flow. The path stretching requirement indicated ($\Delta \ell$) is based on the average ground speed expected over the leg length resulting from employment of a speed reduction command in conjunction with the delay maneuver.

3.1.2 Delay Fan Geometry

A typical delay fan and the straight line approximation used for plotting convenience is illustrated in Figure 3.4. The area required for a delay fan is determined by the magnitude of the course change to initiate the maneuver, α, the lateral offset, w, the magnitude of the angle between the final fan course and the base course, β, and the aircraft turning radius. The fan area can be conservatively approximated by a trapezoid with a base, ℓ', equal to the along track distance required for the fan, and with sides oriented at angles of α and β. The derivation of the distance gained in a delay fan is given in Appendix D.

Table 3.1

Maximum Arrival Path Stretching Requirements

New York Terminal Area - SW Flow

Route Segment	Mean IAS	Mean P.A. x 100	Mean TAS	V_a	V_n	V_d	r_t	d_t	Δt_a	ℓ(nm)	$\Delta\ell$(nm)
J209	226	90	270	310	290	279	1.0	1.0	-2	38	8.63
J209/205	200	52	225	265	245	265	0.7	0	-1	21	6.13
J205	215	100	261	301	281	282	1.0	0.6	-2	68	10.05
J203	232	62	264	304	284	268	1.1	1.3	-2	36	7.96
J201	250	120	313	353	333	291	1.0	2.0	-2	41	6.60
J201/202	225	62	256	296	276	268	0.6	1.0	-1	26	4.23
J202	250	100	303	343	323	282	1.0	2.0	-2	17	9.27
L201	250	100	303	343	323	282	1.0	2.0	-2	18	9.15
L202	250	100	303	343	323	282	1.0	2.0	-2	18	9.15
L201/202/205	224	64	256	296	276	269	0.6	1.0	-1	25	4.34
L203	223	90	266	306	286	279	1.0	0.9	-2	37	9.05
L204	218	90	258	298	278	279	1.0	0.7	-2	44	9.89
L203/204	200	50	225	265	245	265	0.7	0	-1	18.5	5.9
E201	217	78	253	293	273	273	1.0	0.7	-2	42	9.55
E202	232	75	270	310	290	273	1.0	1.3	-2	30	8.36
E201/202	200	38	220	260	240	260	0.7	0	-1	10	5.16
E203	250	85	297	337	317	277	1.0	2	-2	13	9.59
E204	250	85	297	337	317	277	1.0	2	-2	26	7.95
E203/204	230	48	258	298	278	265	0.6	1.2	-1	28	3.77
L205	250	120	313	353	333	290	1.0	2.0	-2	31	7.80

Table 3.2

Maximum Arrival Path Stretching Requirements

New York Terminal Area - NE Flow

Route Segment	Mean IAS	Mean P.A. x 100	Mean TAS	V_a	V_n	V_d	r_t	d_t	Δt_a	ℓ(nm)	$\Delta\ell$ (nm)
J201	250	130	318	358	338	295	1.0	2.0	-2	41	6.72
J202	250	130	318	358	338	295	1.0	2.0	-2	16	9.90
J201/202	228	115	283	323	303	288	1.0	1.1	-1	29	4.27
J203	243	113	299	339	319	286	1.0	1.7	-2	41	6.93
J201/202/203	200	85	237	277	257	277	0.7	0	-1	10	5.39
J205	215	95	258	298	278	290	1.0	0.6	-2	68	12.78
J201/202/203/205	200	43	221	261	241	261	0.7	0	-1	21	6.09
J204	240	48	269	309	289	264	1.0	1.6	-2	28	7.73
L201	250	100	303	343	323	283	1.0	2.0	-2	16	9.45
L202	250	115	311	351	331	289	1.0	2.0	-2	18	9.42
L201/202/205	230	64	264	304	284	270	0.6	1.2	-1	25	3.95
L203	223	90	266	306	286	279	1.0	0.9	-2	37	9.05
L204	218	97	264	304	284	282	1.0	0.7	-2	44	9.59
L203/204	200	50	224	264	244	264	0.7	0	-1	21.5	6.2
E201	237	75	276	316	296	273	1.0	2.0	-2	19	9.06
E202	236	75	275	315	295	272	1.0	2.0	-2	29	8.24
E203	250	100	303	343	323	283	1.0	2.0	-2	13	9.82
E204	250	115	311	351	331	289	1.0	2.0	-2	26	8.40
E203/204	220	75	256	296	276	273	1.0	0.8	-2	45	9.1
E201/202	200	38	220	260	240	260	0.7	0	-1	10	5.17
L205	250	137	322	362	342	298	1.0	2.0	-2	31	8.1

Table 3.3

Maximum Arrival Path Stretching Requirements
Miami Terminal Area - East Flow

Route Segment	Mean IAS	Mean P.A. x 100	Mean TAS	V_a	V_n	V_d	r_t	d_t	Δt_a	ℓ (nm)	$\Delta\ell$ (nm)
201	250	90	298	338	318	279	1.0	2.0	-2	22	8.57
202	250	90	298	338	318	279	1.0	2.0	-2	20	8.81
201/202	216	72	251	291	271	272	.7	.6	-1	31.5	4.97
203	250	100	303	343	323	282	1.0	2.0	-2	20.5	8.83
204	250	100	303	343	323	282	1.0	2.0	-2	20.5	8.83
203/204	207	79	243	283	263	275	.7	.3	-1	35	6.29
205	250	90	298	338	318	279	1.0	2.0	-2	20	8.81
206	250	90	298	338	318	279	1.0	2.0	-2	20	8.81
205/206	233	70	270	310	290	271	.6	1.3	-1	20	4.02
207	250	85	296	336	316	277	1.0	2.0	-2	21.5	8.55
208	250	85	296	336	316	277	1.0	2.0	-2	21.5	8.55
207/208	200	50	224	264	244	264	.7	—	-1	13.5	5.10
209	250	85	296	336	316	277	1.0	2.0	-2	21	8.61
210	250	85	296	336	316	277	1.0	2.0	-2	21	8.61
209/210	250	60	284	324	304	268	.6	2.0	-1	13	4.42

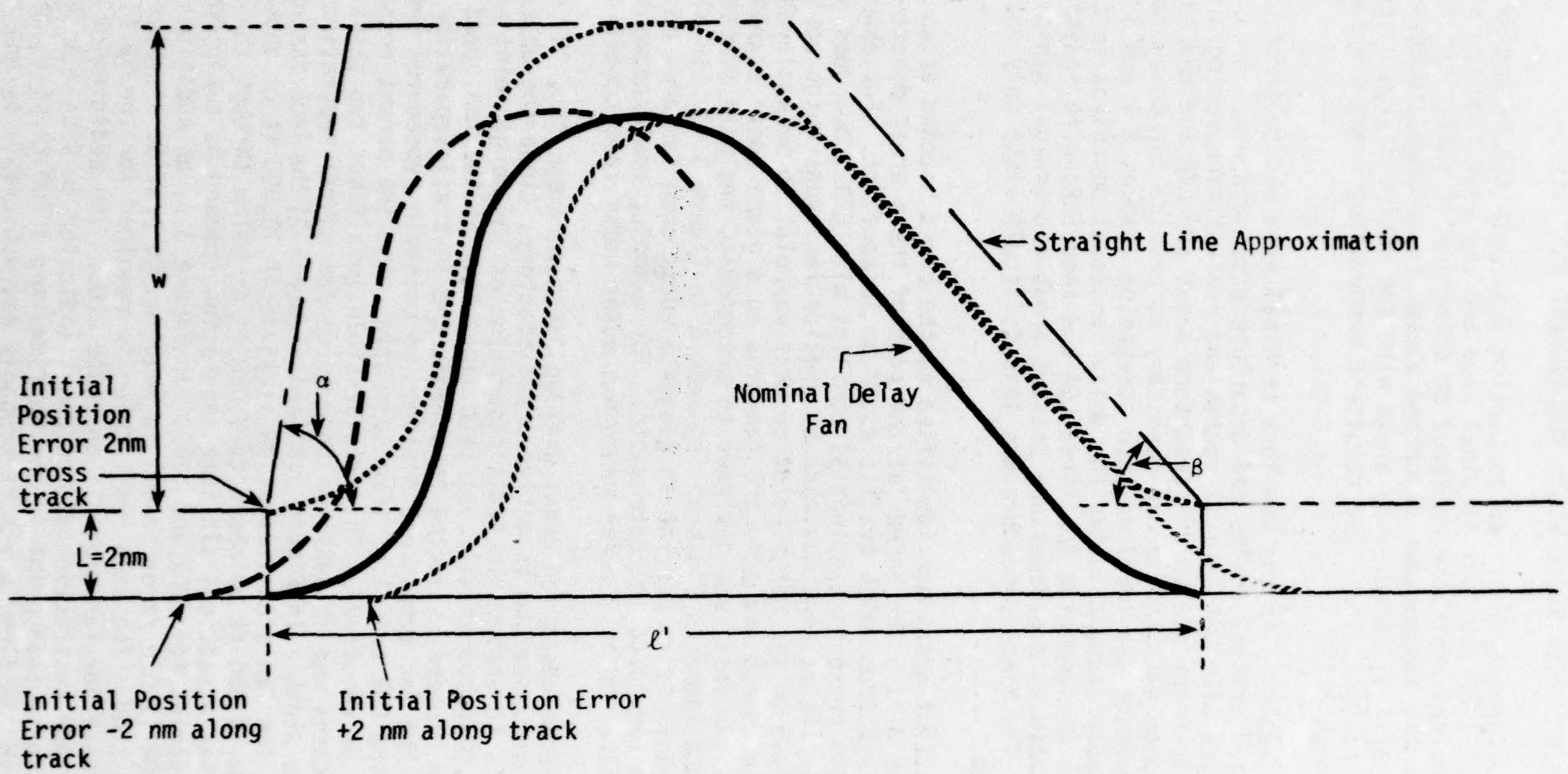


Figure 3.4 Delay Fan Area Approximation

3.2 TERMINAL AREA ROUTE WIDTH REQUIREMENT ANALYSIS

Following the approach described in Section 3.1, both the NE and SW flow designs for the post-1982 New York terminal area and the east flow for the post-1982 Miami terminal area were analyzed to determine if sufficient airspace exists, under the assumptions described above, to accommodate departure passing routes and arrival maneuvering areas with the entire design based on AC 90-45A required route widths. The resultant maneuvering areas are plotted in Figures 3.5 through 3.11.

The procedure employed in the New York terminal area was to first plot the JFK departure and arrival routes and departure passing areas. Areas of of potential conflict with JFK arrival routes and arrival maneuvering areas were then plotted by reference to JFK departure areas and LGA and EWR routes. The remaining airspace was utilized as necessary to provide for delay fans and trombones to accommodate the required path stretching (Tables 3.1 and 3.2) for each JFK arrival route segment, using the delay fan model described in Section 3.1. The procedure was repeated for first LGA and then EWR, with additional conflict areas created by the departure passing areas and arrival maneuvering areas identified. The Miami procedure was less difficult since only one airport was considered.

Potential conflict areas are identified by the cross hatched areas in Figures 3.5 through 3.11. The arrows at the edge of these areas denote the direction of interest from which traffic would be in conflict. For example, in Figure 3.10, L204 presents a potential conflict with E202, but does not conflict with E201. An attempt was made to provide fan areas which would allow a "direct-to" command to the merge point or next waypoint to be employed. Where it was not possible to achieve adequate fan area on a given route segment, the fan area on the next segment was designed to accommodate the path stretching requirements of both segments (such as fan area B in Figure 3.6). In all of such cases, the inability to provide an adequate worst case fan area could not be alleviated by a reduction in route width. For example, route segment L204 in Figure 3.6 requires up to 3 delay maneuvers under worst case conditions.

Note that in some cases fan areas overlap, such as areas "G", "H" and "J" in Figure 3.6. This procedure is entirely satisfactory, since the objective of the fan maneuver is to achieve in-trail separation at the merge point and traffic on the merging routes will maintain separation in the fan areas if the fan geometries are properly selected to achieve the in-trail separation after the merge point. The fan areas were designed to maintain procedural separation between JFK, LGA and EWR traffic. (Fan separation from the parent route was not considered to be required). This was possible in all but two cases, and in neither of these cases was it possible to provide procedural separation through reduction in route width. In Figure 3.8 (and Figure 3.9) the J202 fan area overlies route L202. The fan area lies at an altitude of 10,000 ft or above, and L202 descends from 10,000 ft or above to 9,000 ft or below through the J202 fan area, requiring that a tactical altitude separation command be employed at the common arrival waypoint for J202 and L202. In Figure 3.6, an additional altitude restriction on J304 (7,000 ft or below) is required to provide airspace for fan area "N" on route L203. The same restriction is required for the SW flow (Figure 3.8) to provide space for fan area "F" on route J205. The addition of a procedural, or tactical, altitude restriction at the point indicated on J304 imposes a 281 ft/mi climb ceiling to that point in the NW flow, and a 700 ft/mi climb ceiling to that point in the SW flow, which is probably not achievable by any civil aircraft.

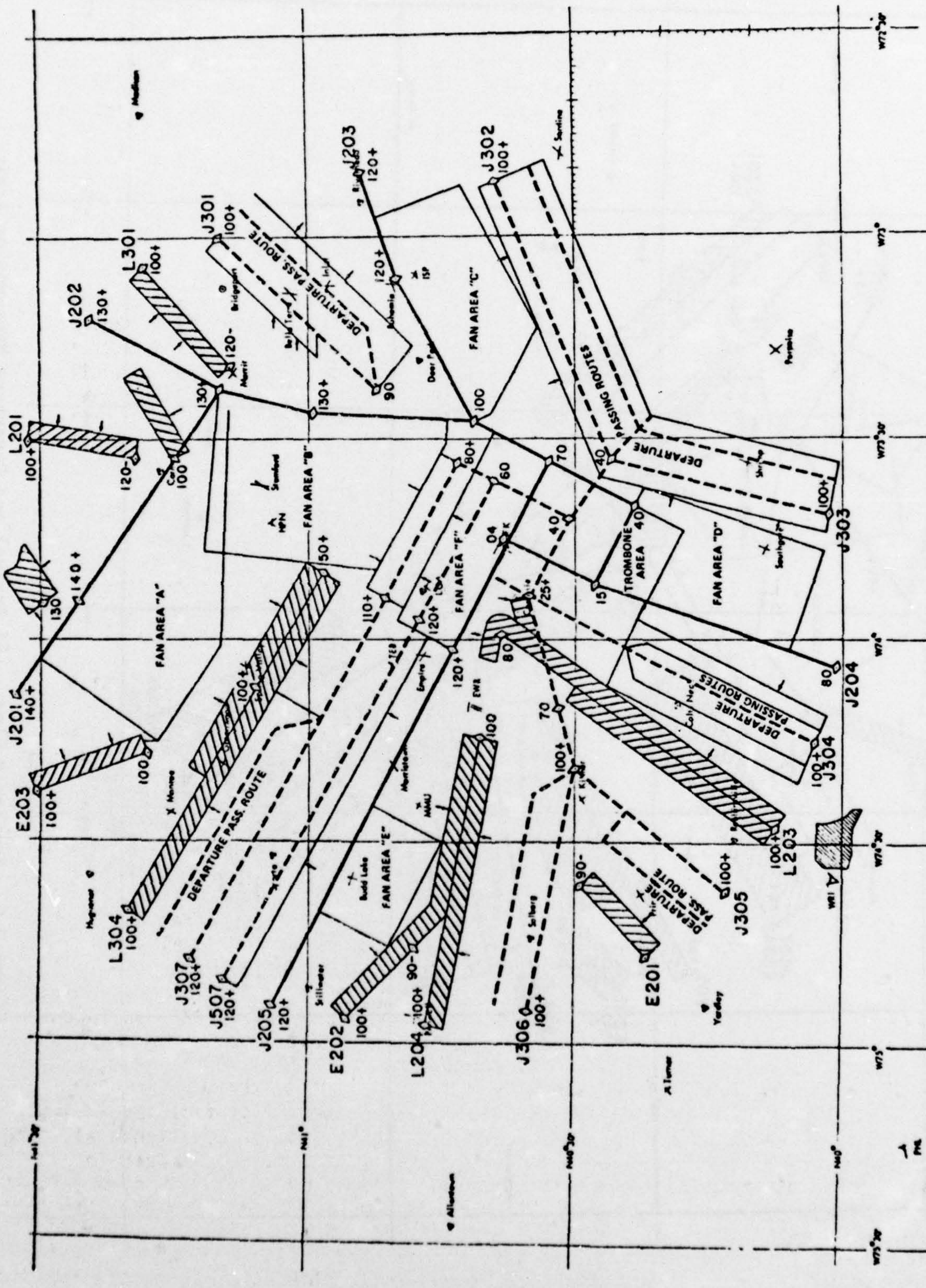


Figure 3.5 Northeast Flow - JFK Arrival and Departure Maneuvering Areas

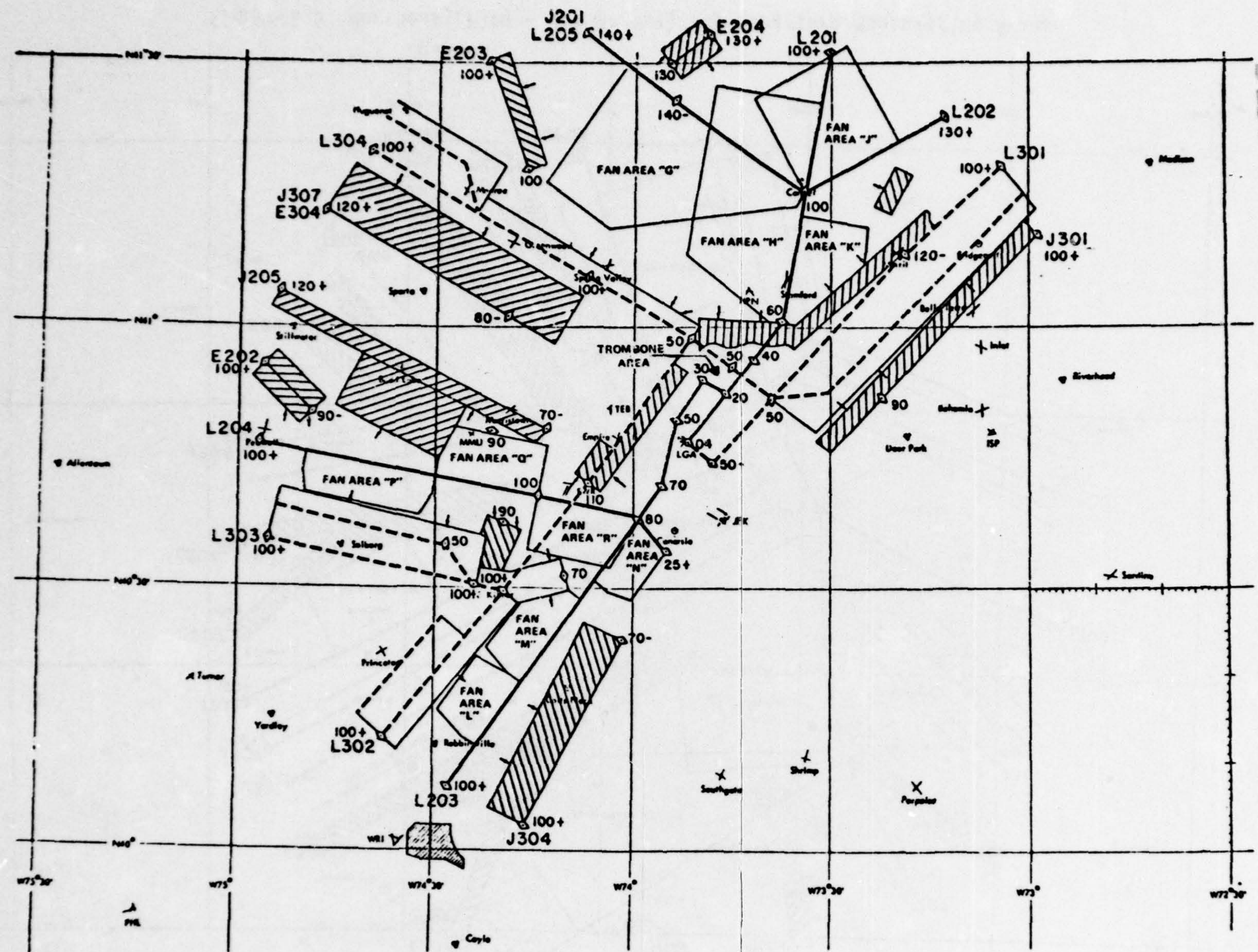


Figure 3.6 Northeast Flow - LGA Arrival and Departure Maneuvering Areas

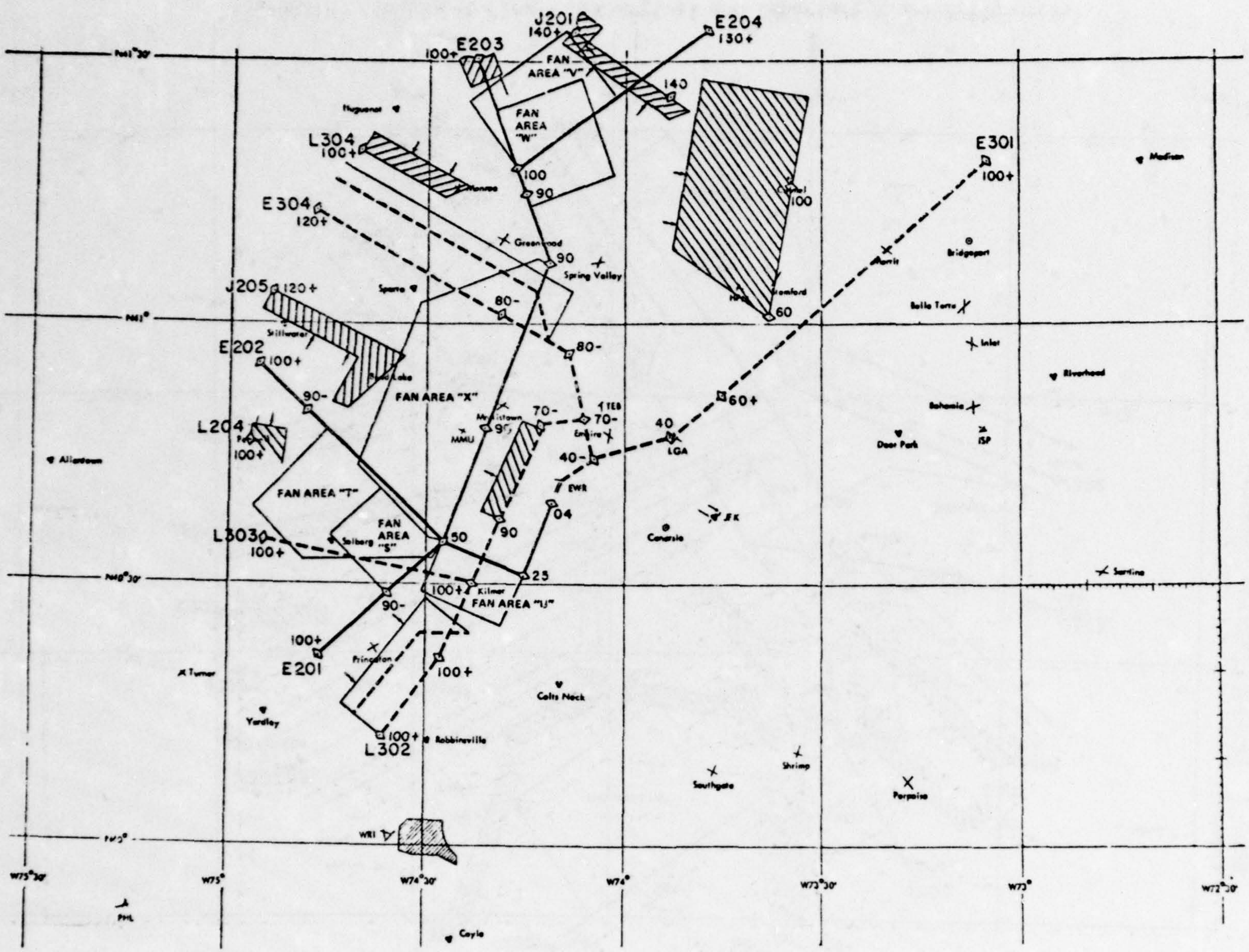


Figure 3.7 Northeast Flow - EWR Arrival and Departure Maneuvering Areas

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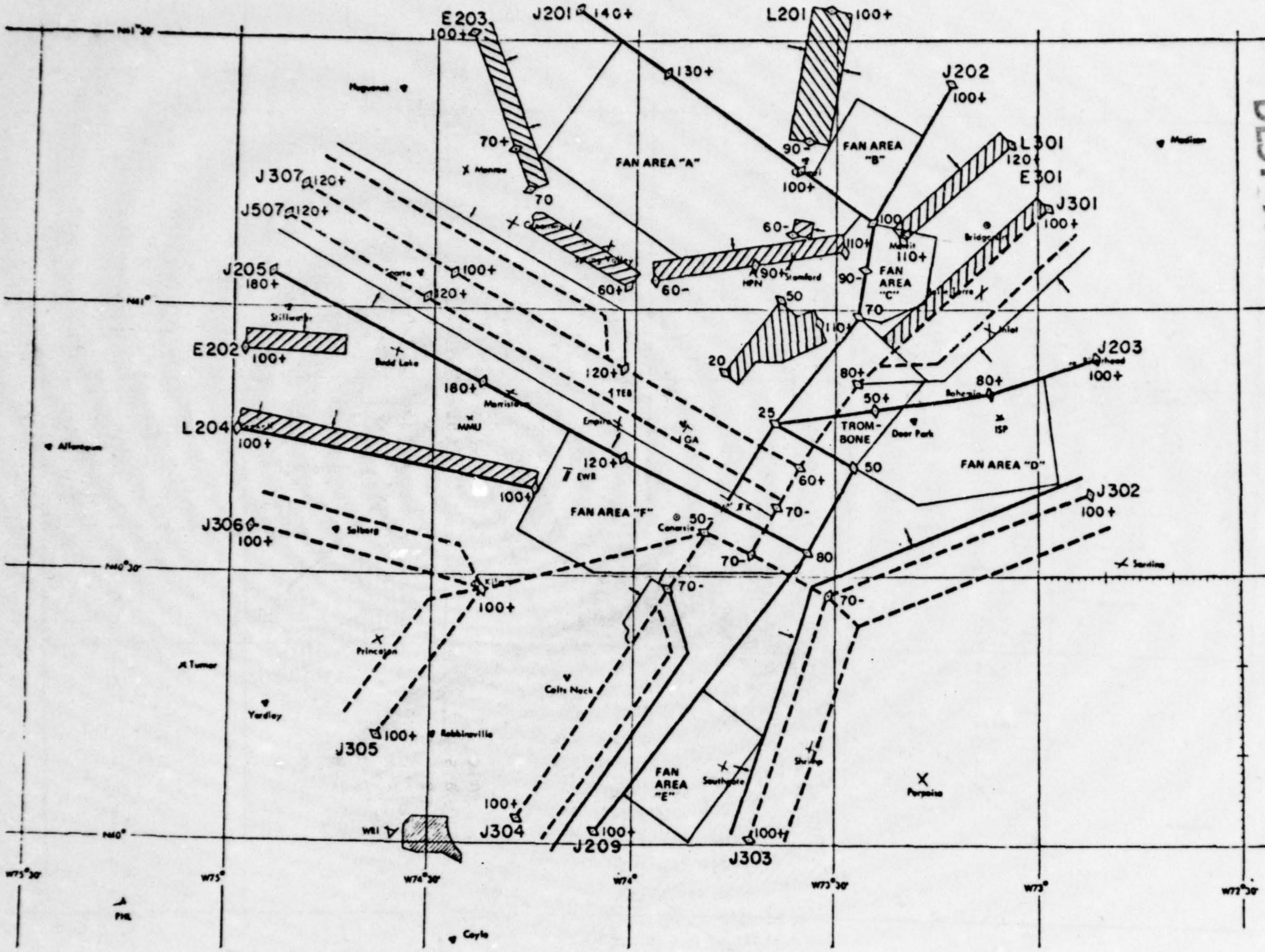

Figure 3.8 Southwest Flow - JFK Arrival and Departure Maneuvering Areas

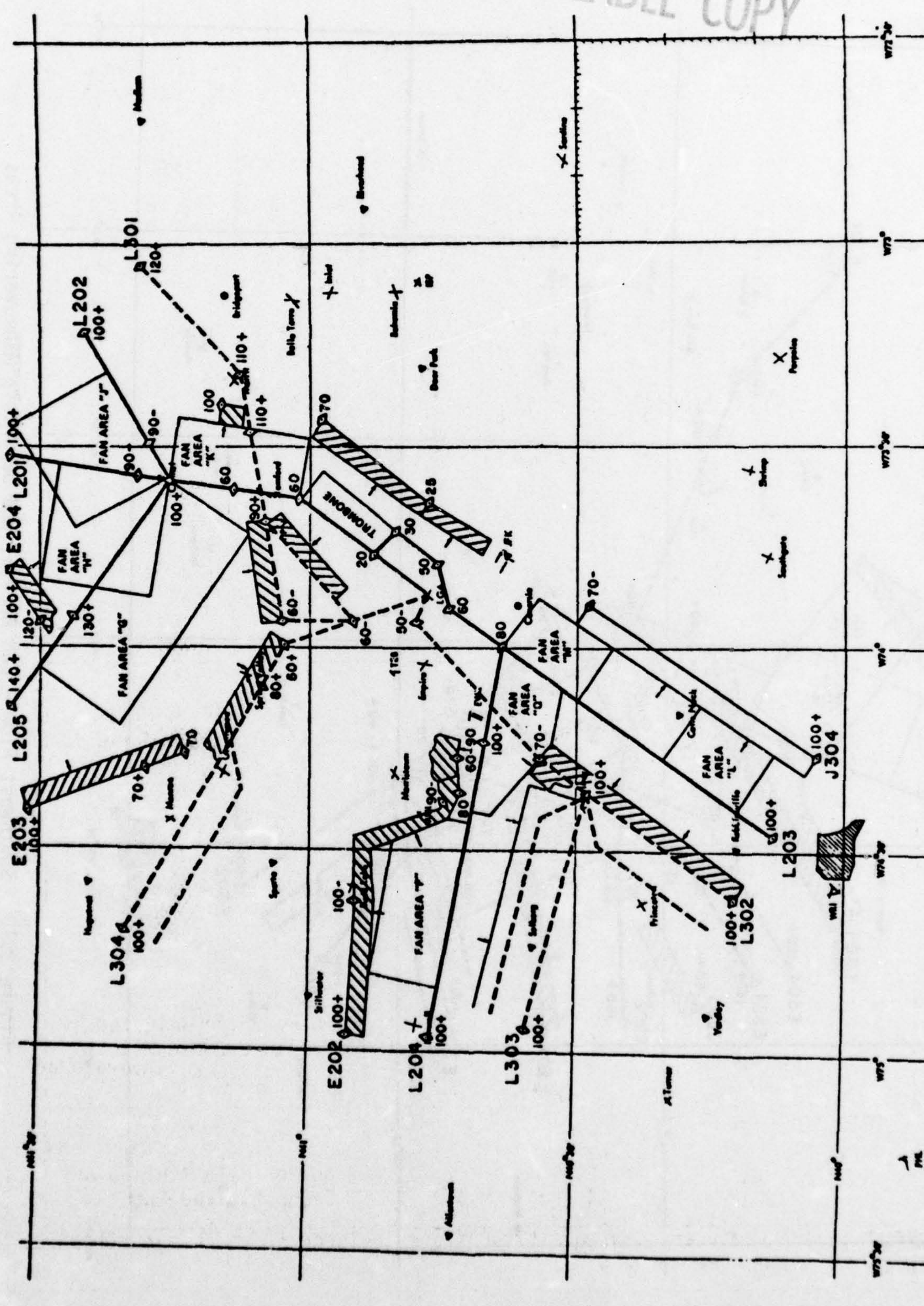

Figure 3.9 Southwest Flow - LGA Arrival and Departure Maneuvering Areas

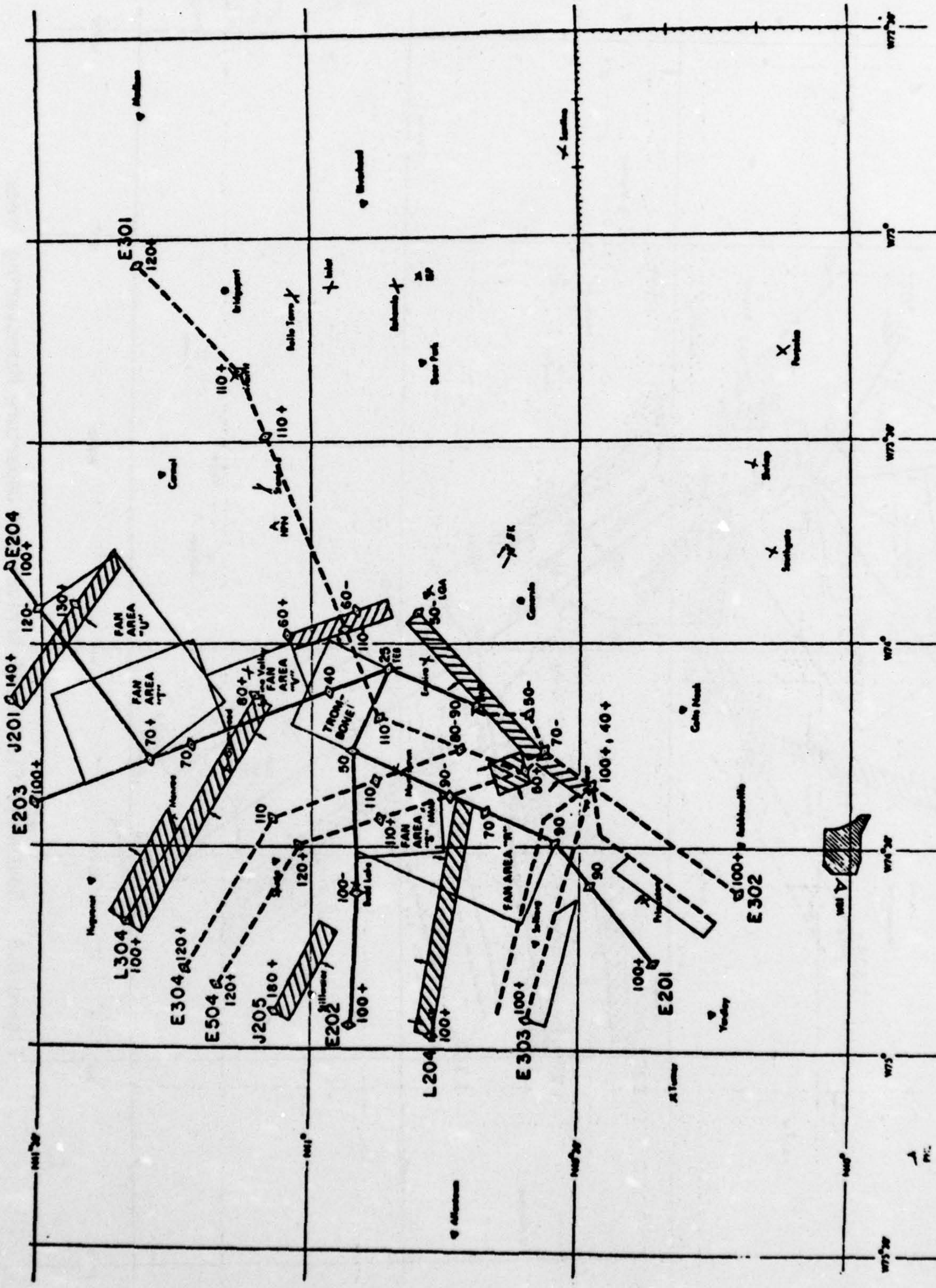

Figure 3.10 Southwest Flow - EWR Arrival and Departure Maneuvering Areas

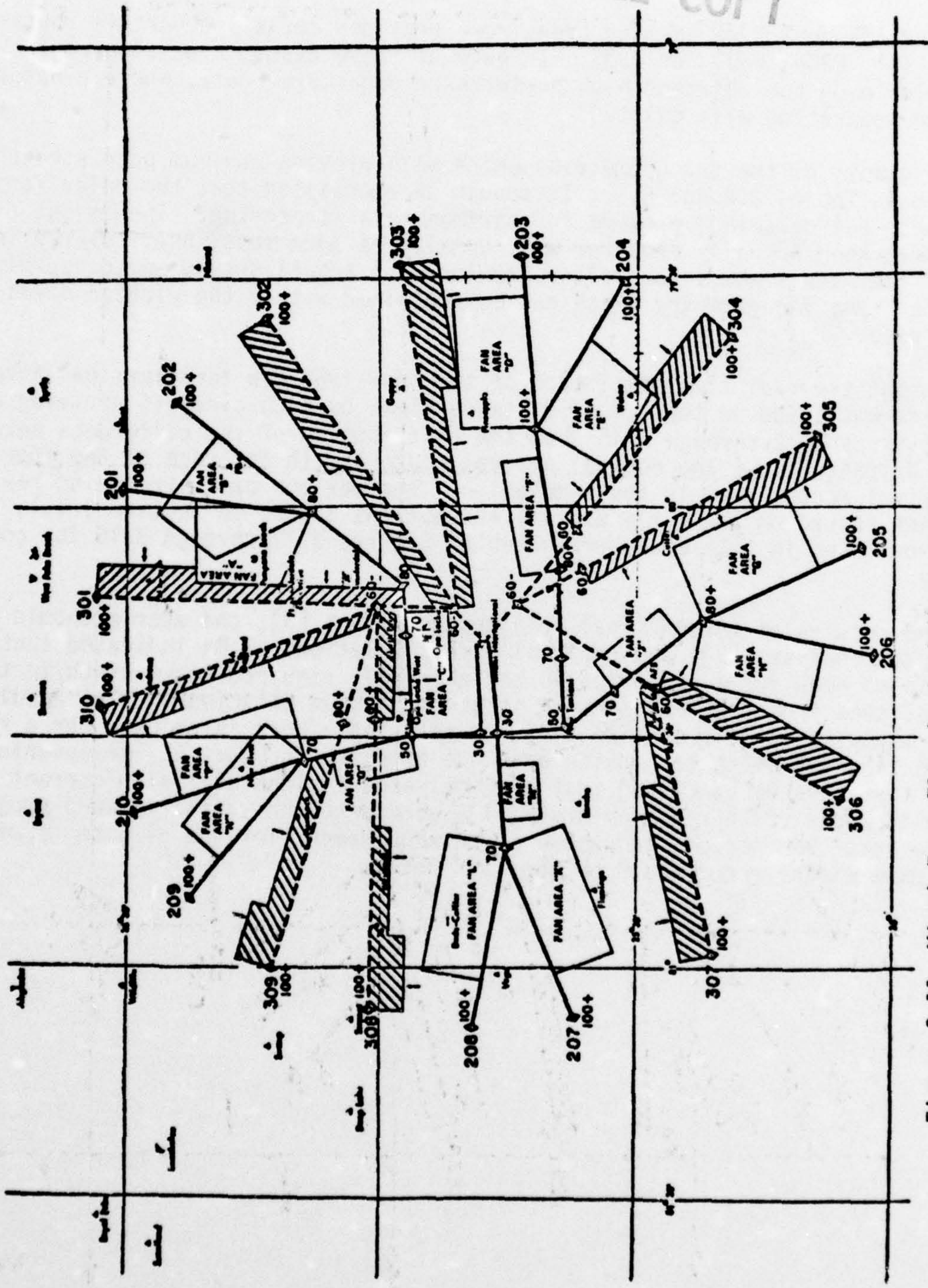

Figure 3.11 Miami East Flow Arrival Maneuvering Areas

Discrete departure passing areas were provided for all departure routes except E301, E304, L301 and J307. In each of these cases, a passing route is available on the adjacent high performance departure route, where a natural altitude separation will exist.

A summary of the fan geometries which will provide maximum path stretching is given in Tables 3.4 and 3.5. It should be emphasized that the delay fans (or trombones) described provide for maximum path stretching. The amount of path stretching actually required will usually be much less, particularly in ARTS III terminals where controller knowledge of actual ground speed is fairly accurate. Any fan geometry which can be contained within the plotted areas can be used.

During the real time simulation of the post-1982 New York terminal area [8], data was taken on the actual distance flown by each aircraft arriving at JFK. Figures 3.12 through 3.15 show the distribution of the difference between actual distance flown and nominal arrival route length for each of the four JFK arrival routes used in the simulation. The maximum path stretching requirement, based on the early arrival assumptions listed in Section 3.1.1, which were used in this study are shown on Figures 3.12 through 3.15 for comparison.

The results of the terminal area design effort [3], the user economic and ATC impact analyses [5], and the real time simulations [7,8] indicated that there is no need for a reduction in the currently required route width in the terminal area from the viewpoint of strategic design efficiency. The results of the analysis in this section also indicate that there is no need for a reduction in route width to provide adequate airspace for tactical maneuvering. It may therefore be concluded that terminal area designs utilizing current AC 90-45A route width requirements will accommodate the traffic demand projected for the post-1982 period, and there is no requirement for the ± 1.5 nm terminal area route widths recommended by the Task Force.

Table 3.4

Maximum Length Delay Fans

New York Post-1982 Terminal Area - Route Width = ±2 nm

Flow	Airport	Fan Area	Route Segment	TAS (knots)	α (deg.)	β (deg.)	ℓ' (nm)	w (nm)	Δx (nm)	Δℓ (nm) avail.	Δℓ (nm) required
NE	JFK	A	J201	255	90	32	33	14.1	5.2	16.3	6.7
		B	J201/202	248	90	67	25	16.0	11.8	24.3	4.3
		B	J202+J201/202	255	90	67	25	16.0	11.5	24.2	14.2
		C	J203	246	90	57	25	9.2	13.2	12.2	6.9
		Trombone	J201/202/203							>20	5.4
		D	J204	224	90	84	22	10.5	14.9	17.6	7.7
		E+F	J205	250	90/90	90/90	11/23	6.5/5.0	3.1/15.2	9.6+6.6	12.8
NE	LGA	G	L205	258	90	40	25	13.2	3.6	16.1	8.1
		H	L201+L201/202/205	235	90	62	25	10.1	14.1	14.3	13.4
		J	L202	249	90	90	12	10.0	4.3	16.7	9.4
		K	L201/202/205	230	90	39	12	6.0	0.1	6.6	5.4
		L+M+N	L203	239	77/77/77	77/40/77	8.3/11.3/8.5	4.0/3.4/3.2	0.8/2.3/1.3	10.9	9.1
		P+Q+R	L204	242	70/85/72	85/65/72	12/12/13	4/4/3	4.3/4.1/5.7	11.9	9.6
		Trombone	L203/204							>20	6.2
NE	EWR	S	E201	233	90	87	8.5	7.5	1.5	11.9	9.1
		T	E202	232	90	42	18.2	10.0	2.4	12.3	8.2
		U	E201/202		90	90	8	4.5	3.5	5.5*	5.2
		V	E204	249	90	90	20	7.7	12.3	12.1	8.4
		W	E203	243	90	90	11.5	8.0	4.1	12.8	9.8
		X	E203/204	233	50	68	33	10.0	16.7	10.7	10.0
SW	JFK	A	J201	251	90	45	33	13.6	13.8	17.4	6.6
		B	J202	242	90	84	11.8	7.3	4.1	11.1	9.3
		C	J201/202	228	90	55	11.0	5.2	2.4	6.2	4.2
		D	J203	228	90	46	30	8.3	17.4	10.3	7.8
		Trombone	J205/209							>20	6.1
		E	J209	239	90	90	14.5	6.5	7.4	9.9	8.6
		F	J205	242	90	27	30	10.0	5.8	10.8	10.1
SW	LGA	G	L205	250	90	90	25	9.0	17.2	14.6	7.8
		H	L201	242	90	90	11.8	13.7	4.5	24.3	9.2
		J	L202	242	90	90	11.5	9.8	4.2	16.5	9.2
		K	L201/202	229	90	90	15	4.2	8.5	5.6	4.3
		L+M	L203	239	90/90	90/90	10/10	5.3/5.3	2.9/2.9	15.2	9.1
		P+Q	L204	239	90/25	60/65	18/18	5.7/5.3	9.1/1.1	11.1	9.9
		Trombone	L203/204							>20	5.9
SW	EWR	R	E201	233	90	64	24	8.0	14.6	11.1	9.6
		S	E202	233	90	64	12	8.0	2.6	11.1	8.4
		Trombone	E201/202							14.0	5.2
		T	E203	237	90	90	16.5	8.0	9.5	13.0	9.6
		U	E204	237	90	90	20	8.0	13.0	13.0	8.0
		V	E203/204	225	90	90	10	4.2	3.7	5.7	3.8

Table 3.5

Maximum Length Delay Fans
Miami Post-1982 Terminal Area
Route Width Conforming to AC90-45A

Route Segment	Fan Area	TAS (knots)	α (deg.)	β (deg.)	ℓ' (nm)	ω (nm)	$\Delta\chi$ (nm)	$\Delta\ell$ (nm)	
								avail.	required
201	A	239	80	72	13.5	9.5	3.2	13.2	8.57
202	B	239	90	67	14.0	11.0	3.4	16.2	8.81
201/202	C	232	90	90	8.0	5.0	1.3	7.1	4.97
203	D	242	90	90	15.2	6.5	7.9	9.9	8.83
204	E	242	80	90	12.2	9.1	3.9	14.1	8.83
203/204	F	235	90	90	13.3	5.0	6.4	7.0	6.29
205	G	239	90	90	14.7	7.2	7.6	11.3	8.81
206	H	239	90	90	14.7	6.3	7.6	9.5	8.81
205/206	J	231	90	90	10.0	4.0	3.3	5.1	4.02
207	K	237	90	90	16.0	7.0	9.0	11.0	8.55
208	L	237	90	90	16.0	7.0	9.0	11.0	8.55
207/208	M	224	90	90	6.6	4.0	0.3	5.3	5.10
209	N	237	90	90	15.1	6.0	8.1	9.0	8.61
210	P	237	90	90	15.1	7.0	8.1	11.0	8.61
209/210	Q	228	90	90	9.7	4.0	3.2	5.2	4.42

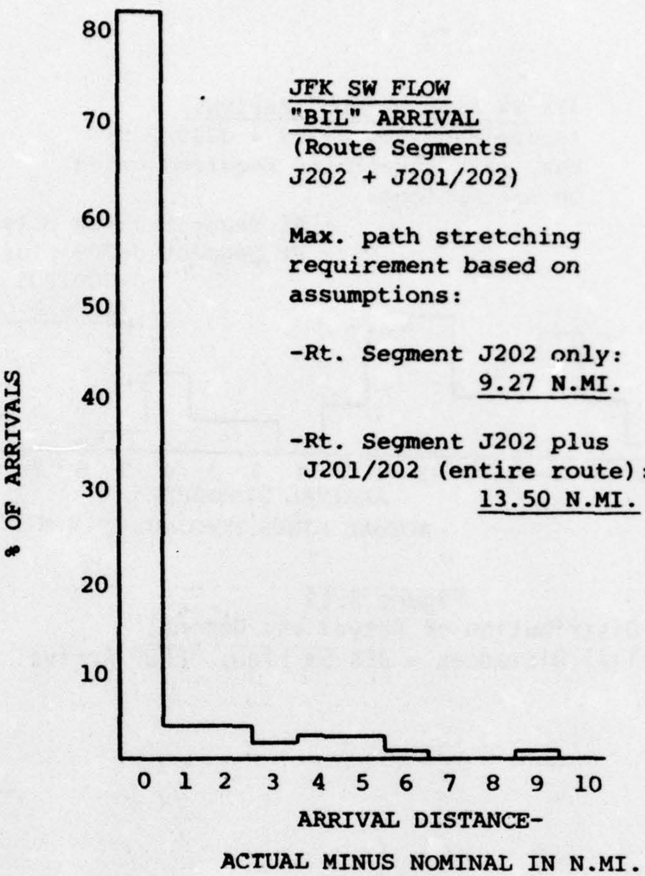

Figure 3.12 Distribution of Actual vs Nominal Arrival Distances-
JFK SW Flow, "BIL" Arrival

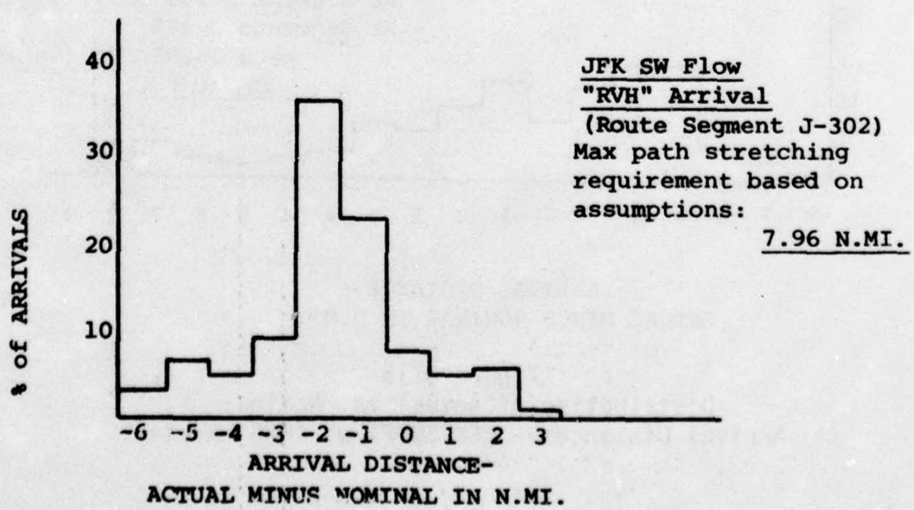

Figure 3.13 Distribution of Actual vs Nominal Arrival Distances-
JFK SW Flow, "RVH" Arrival

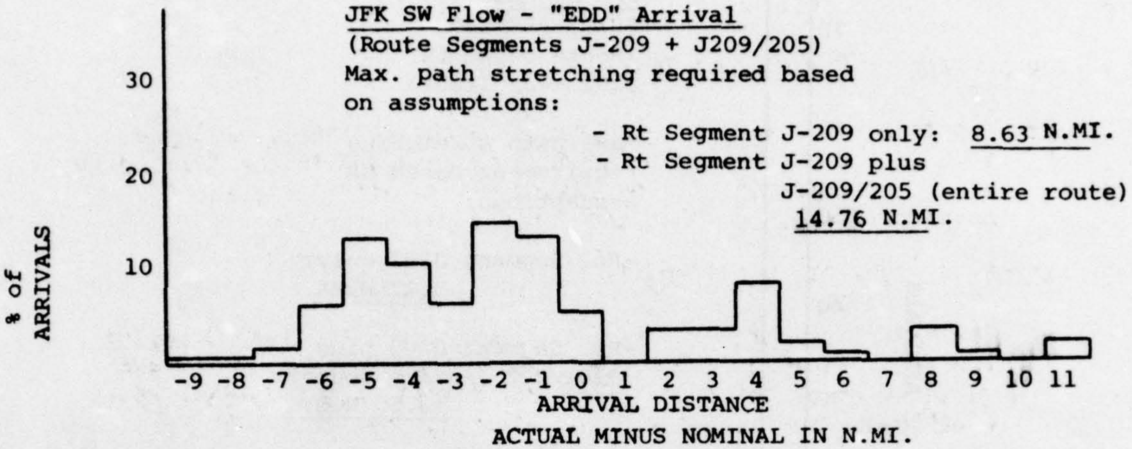

Figure 3.14
Distribution of Actual vs. Nominal
Arrival Distances - JFK SW Flow, "EDD" Arrival

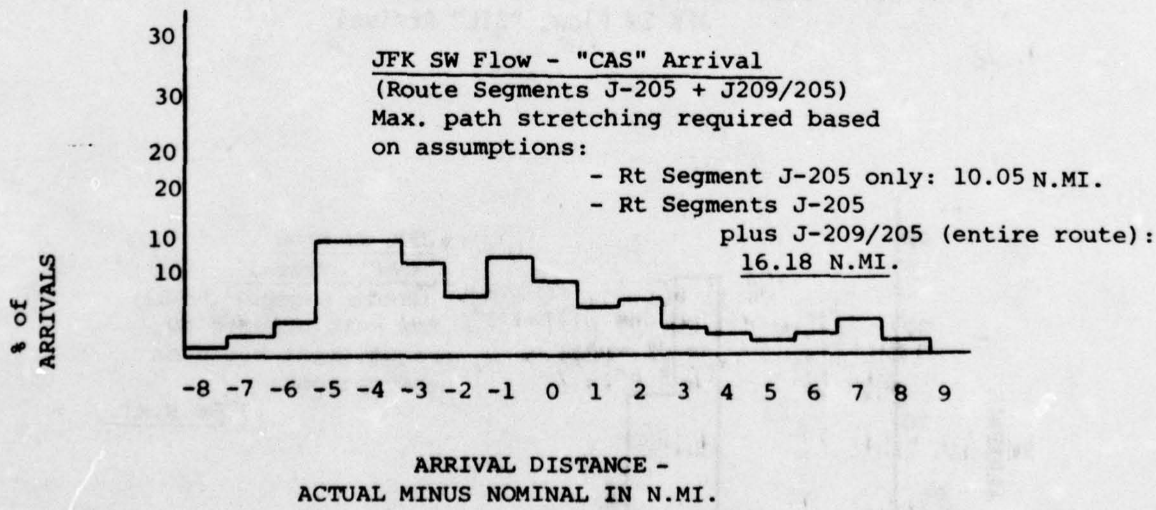

Figure 3.15
Distribution of Actual vs. Nominal
Arrival Distances - JFK SW Flow, "CAS" Arrival

4.0 CONCLUSIONS

4.1 ENROUTE AND TERMINAL ROUTE DESIGN

- Constant route widths, as opposed to the currently employed splayed routes, are required both enroute and in the terminal area to provide for the necessary design efficiency and to maximize the use of non-radar procedural separation.

4.2 ENROUTE ROUTE WIDTH REQUIREMENTS

- The RNAV Task Force accuracy recommendation for 1977 provides for a constant ±4.0 nm route width. This route width is adequate to accommodate the post-1982 traffic and a further route width reduction is not considered necessary.

- A reduction in route widths below ±4.0 nm would result in some reduction in enroute miles between city pairs. The maximum additional economic benefit to the user from these reduced route lengths would be approximately 12% of the benefit already realized through use of RNAV compared with VOR routes.

4.3 TERMINAL AREA ROUTE WIDTH REQUIREMENTS

- The present terminal route width of ±2 nm or ±4 nm, dependent upon orientation and distance from the VORTAC, as required by AC 90-45A, is adequate to accommodate the post-1982 traffic demand, and a route width reduction is not considered necessary.

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APPENDIX A

U.S. TRAFFIC EXCHANGE PATTERNS

One of the fundamental aspects of the Route Width Study was the choice of areas to be studied. With regard to data collection and selection criteria, choice of the high density enroute area presented the most difficulty.

The first part of this selection process was the generation of scatter plots showing approximate aircraft locations at various times during the day. These plots served two primary functions. First, while specific density measures would ultimately be used for final area selection, the density measures had to be computed for pre-defined areas. The scatter plots were used as a tool in defining the candidate areas. Second, the scatter plots provided the most illustrative means to confirm the validity of both the candidate and final area selections.

The scatter plots were generated at hourly intervals from 1200 to 0200 hours GMT (0700 to 2100 hours EST). The following paragraphs describe the means by which this was accomplished and the approximations involved. These approximations apply also to the density measure computations in Appendix B.

The 1969 IFR Peak Day Traffic Tape was used as the traffic sample. This was chosen rather than more recent tapes such as 1970 or 1971, due to its higher traffic level. Consideration was given to the FAA traffic forecasts [2], as used in the MIT Fast Time Simulations. However, these tapes do not contain the fifteen hours of traffic previously mentioned.

The aircraft locations on each plot are based upon two approximations. First, a great circle structure was utilized. This is not intended to reflect the pre-planned direct environment as much as it reflects a demand for airspace. In other words, the traffic patterns evidenced in the plots are not the result of a particular route design, but rather an indicator of where the traffic would like to be (weather effects excluded). The second approximation is that the aircraft along track distances were computed based upon requested true airspeeds and instantaneous acceleration to achieve that speed. This merely has the effect that each aircraft is farther along than would ordinarily be the case, but it has no detrimental effect on the utility of the plots or the resulting exchange patterns.

One comment must be made relative to the total traffic illustrated on the plots. An airport data base of 330 airports was used to determine origin and destination locations. The choice of airports was based upon traffic exchange. It is known that this data base accounts for many more flights than the 211 airports utilized in the MIT fast time simulations although these are not necessarily the same flights. As such, it was considered adequate for this phase of the study. However, 43.3% of the high altitude flights on the IFR tape could not be located and plotted. This percentage seemed high although one must consider the fact that this includes many international departures and military operations which should not be considered.

The plots are presented on the following pages. Also shown are the candidate areas. The areas were chosen based upon the rationale that at some hour they contained traffic which might provide a requirement for diminished route widths. It is apparent from the first plot that not all areas are congested at all hours. The plots of greatest interest are those for hours 22 through 2 GMT.

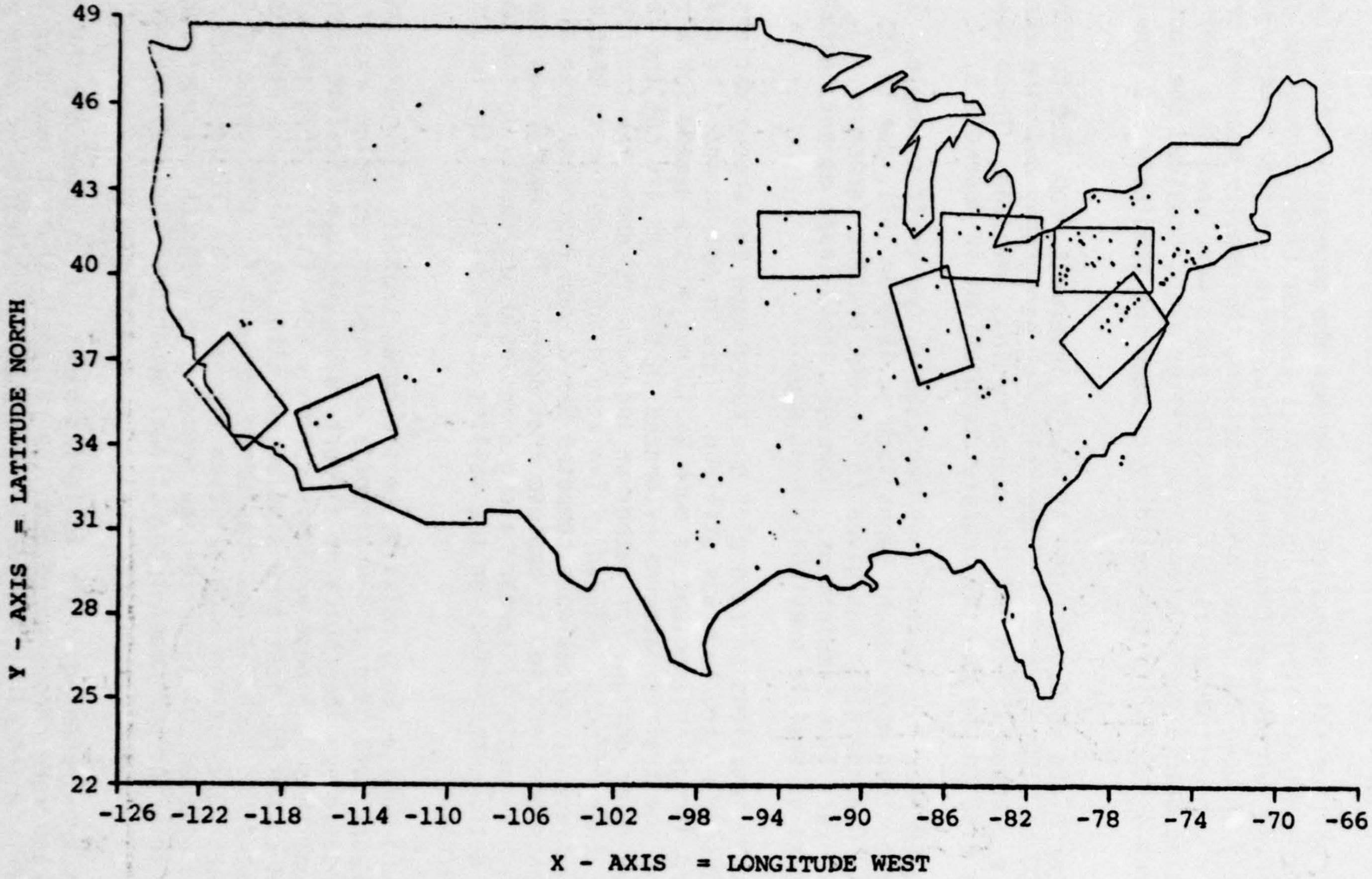

Figure A.1 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 12 GMT)

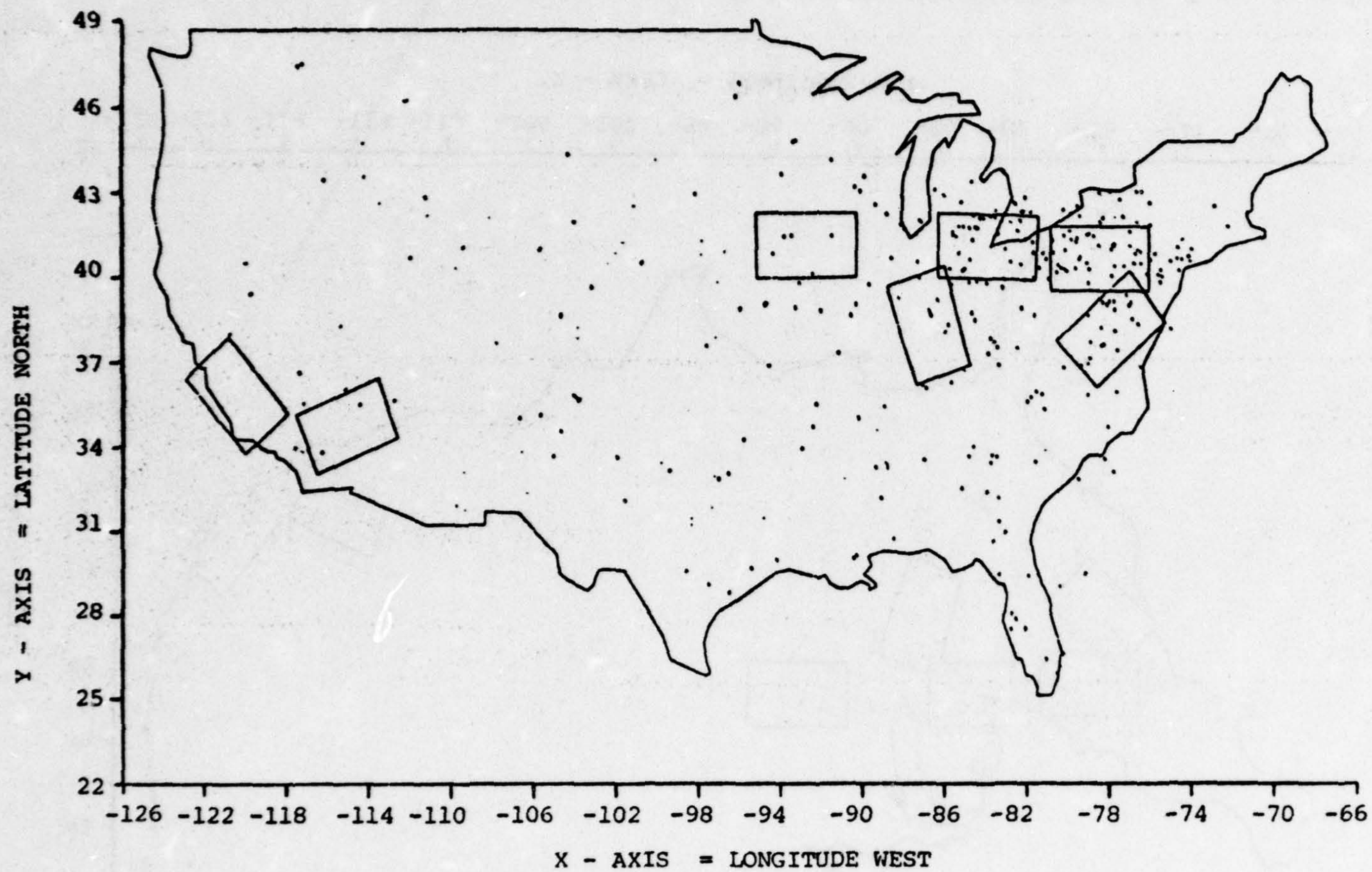

Figure A.2 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 13 GMT)

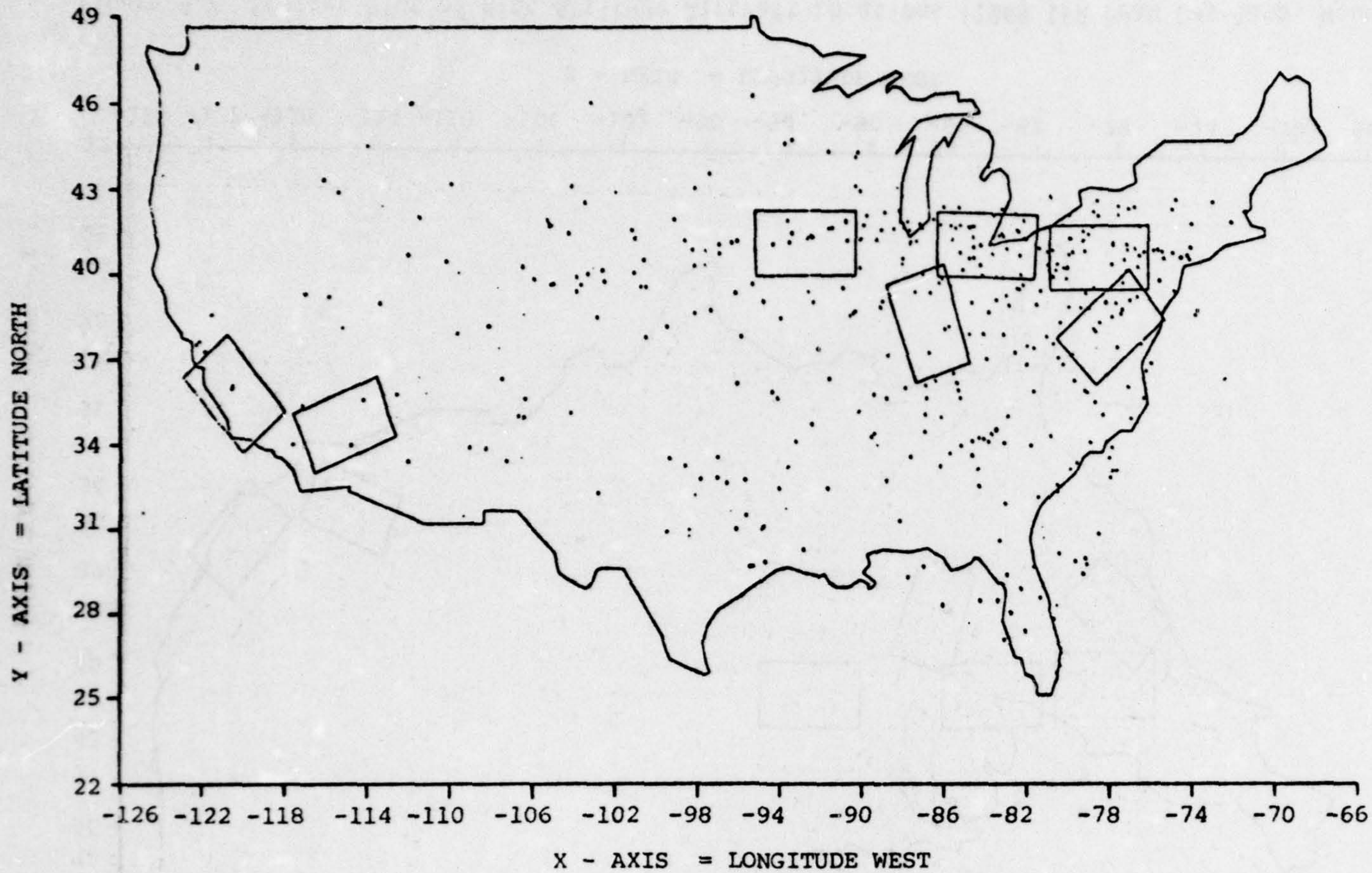

Figure A.3 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 14 GMT)

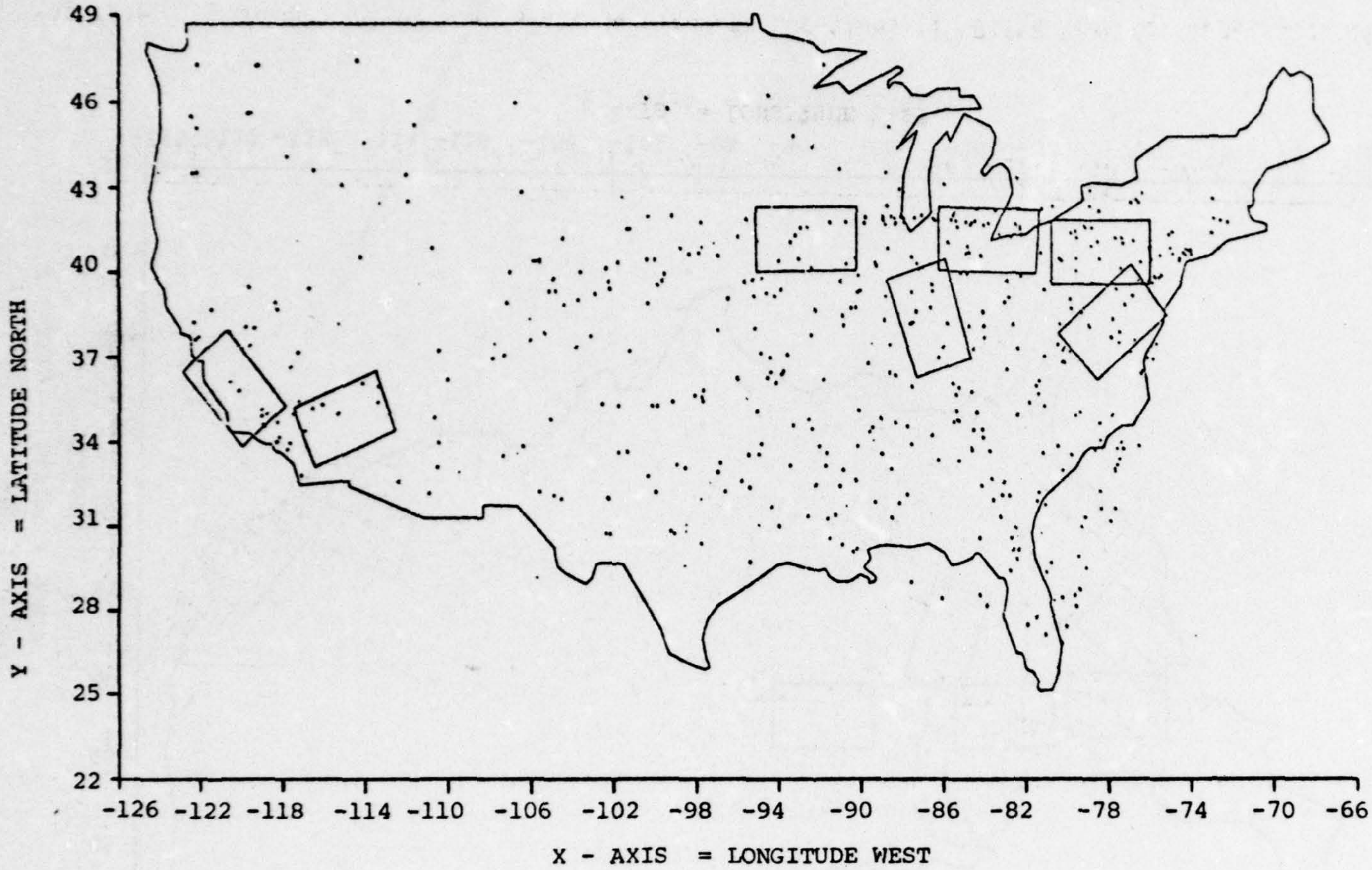

Figure A.4 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 15 GMT)

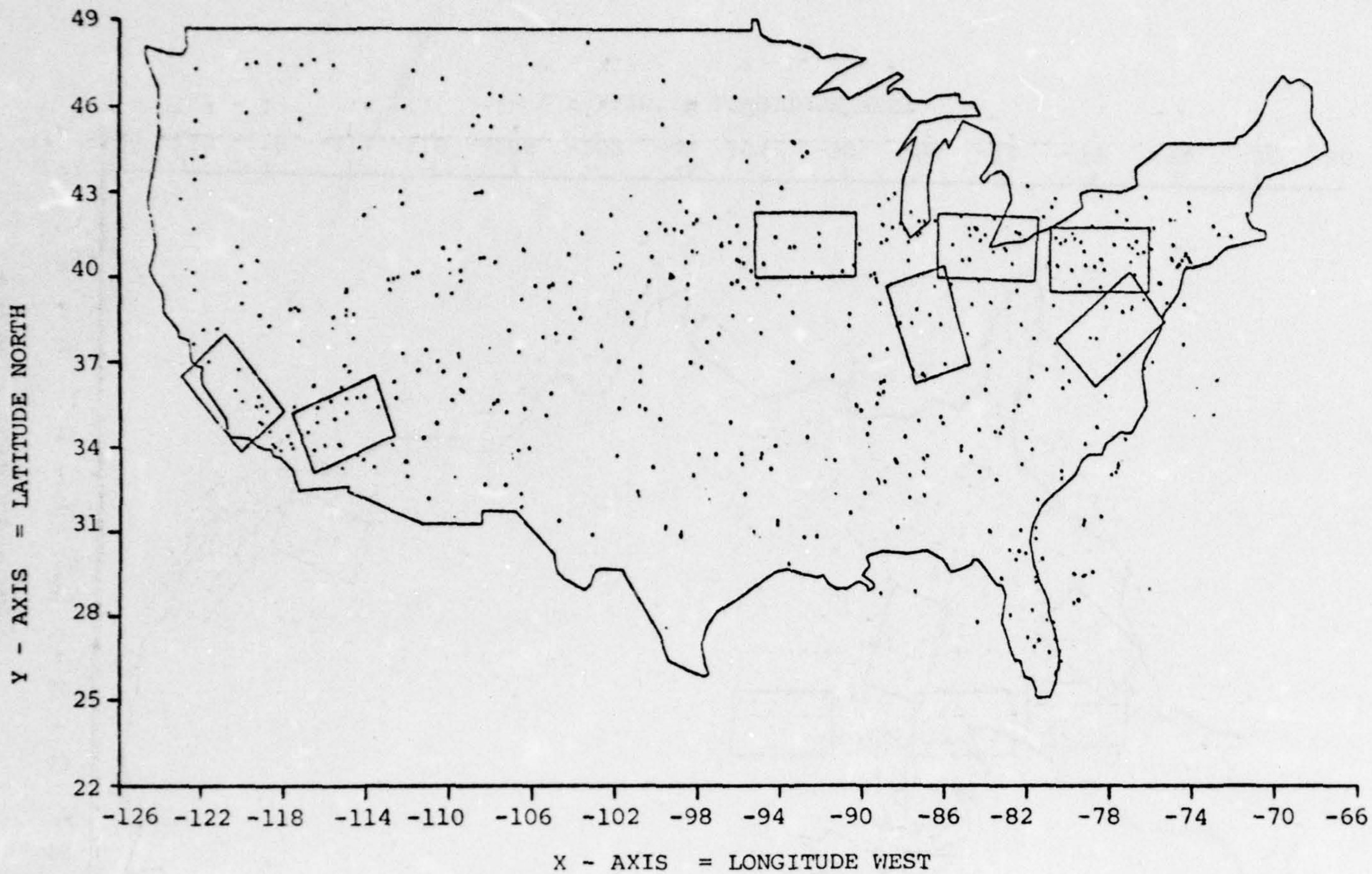

Figure A.5 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 16 GMT)

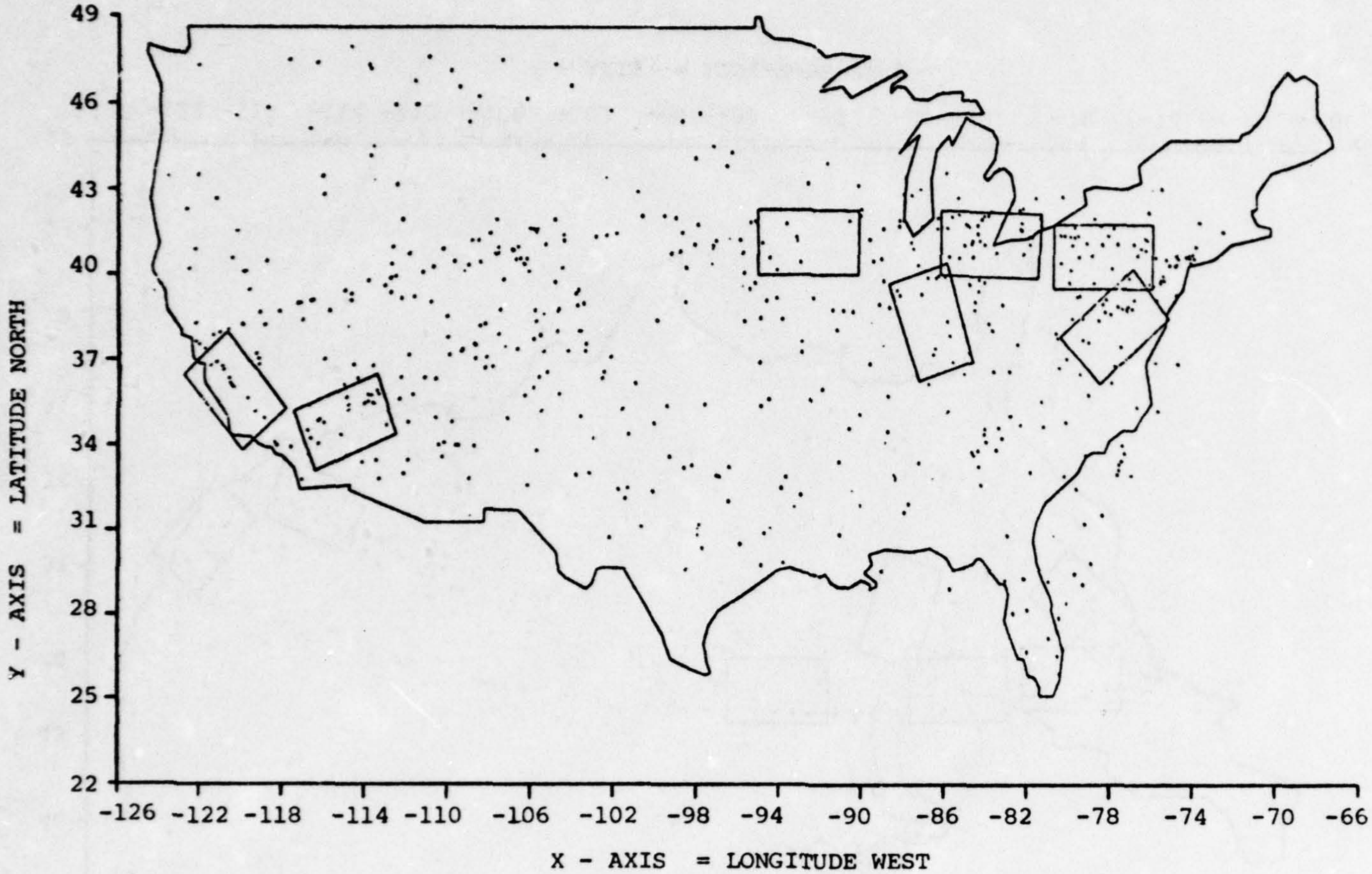

Figure A.6 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 17 GMT)

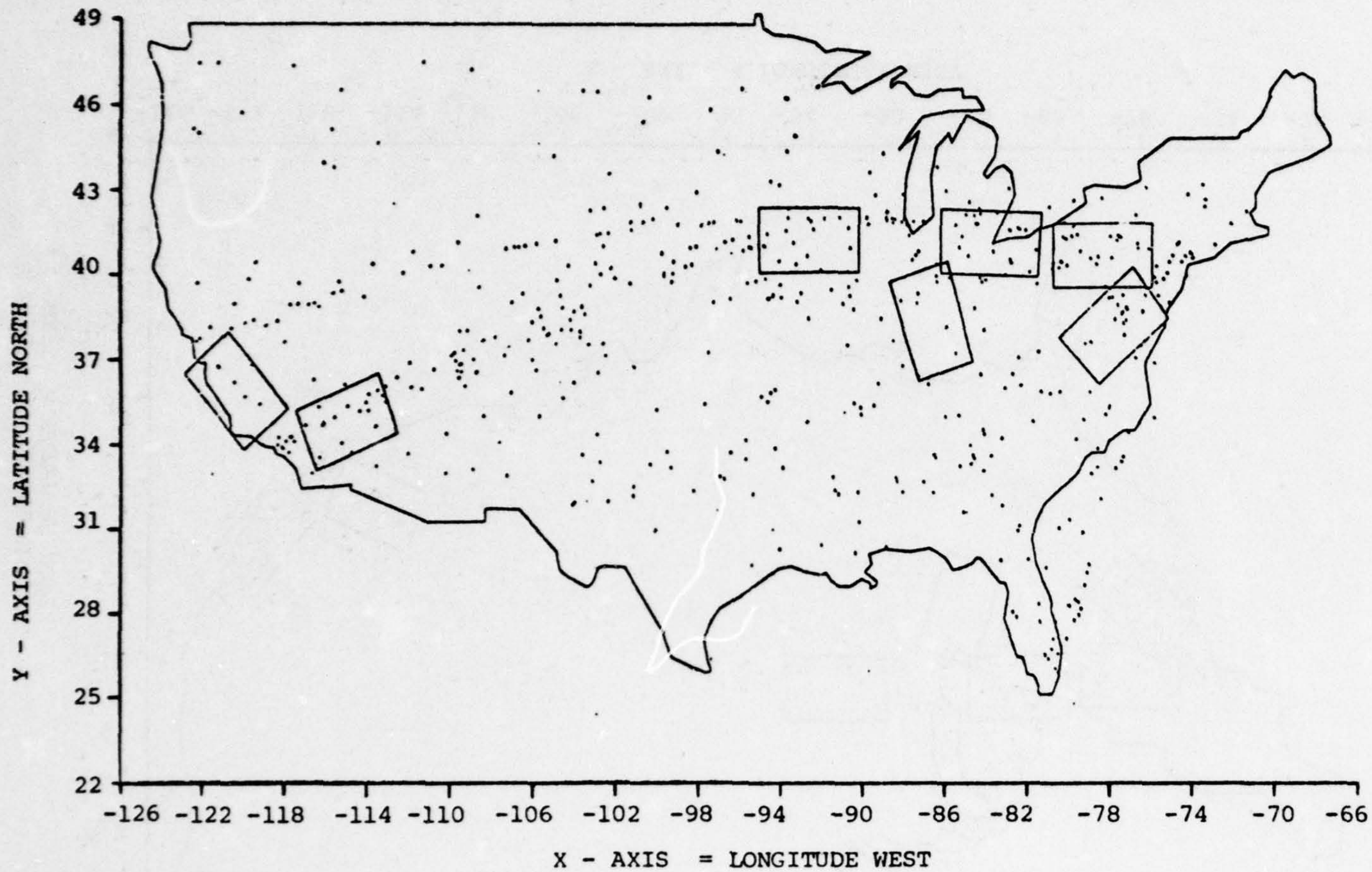

Figure A.7 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 18 GMT)

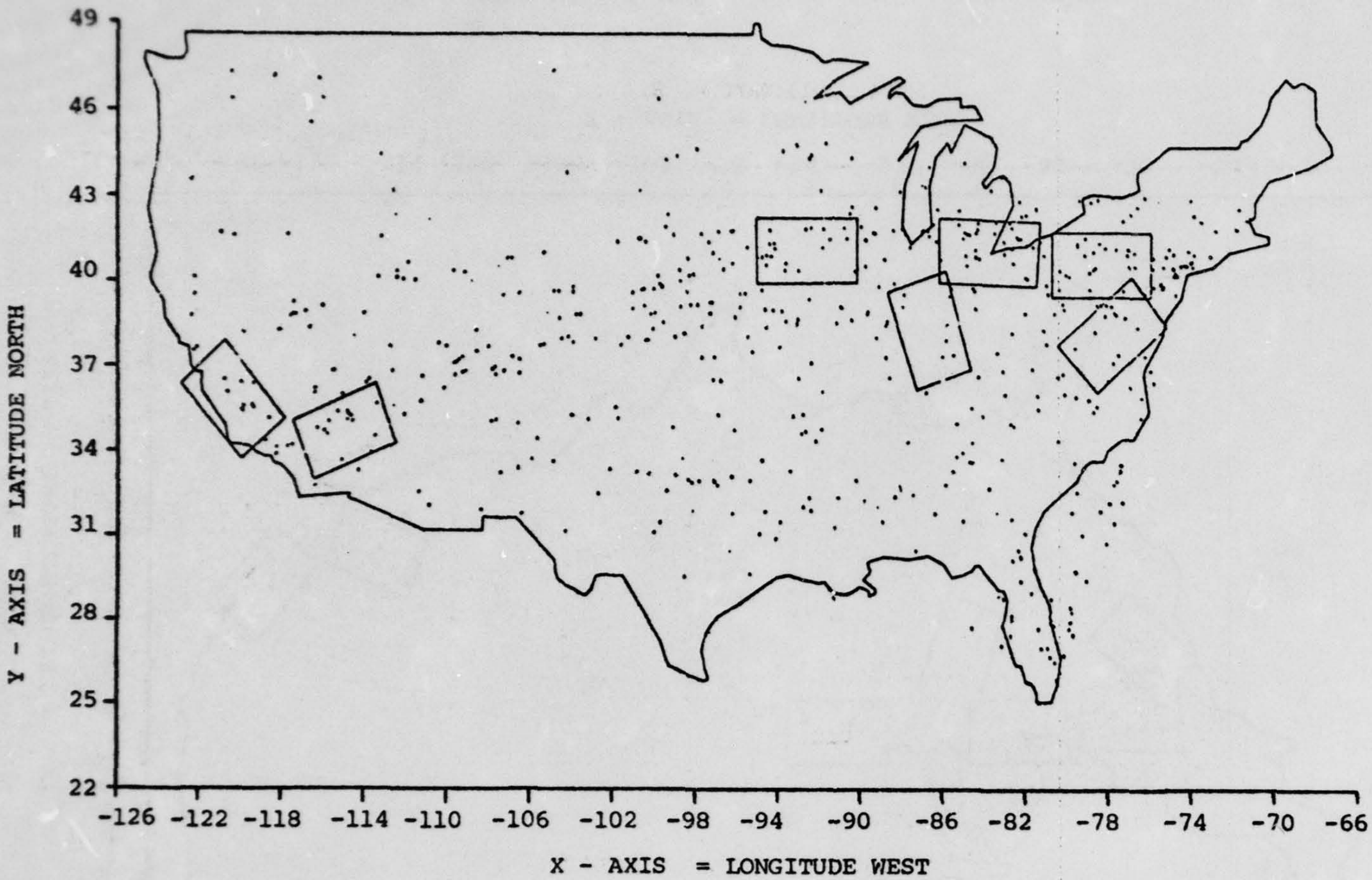

Figure A.8 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 19 GMT)

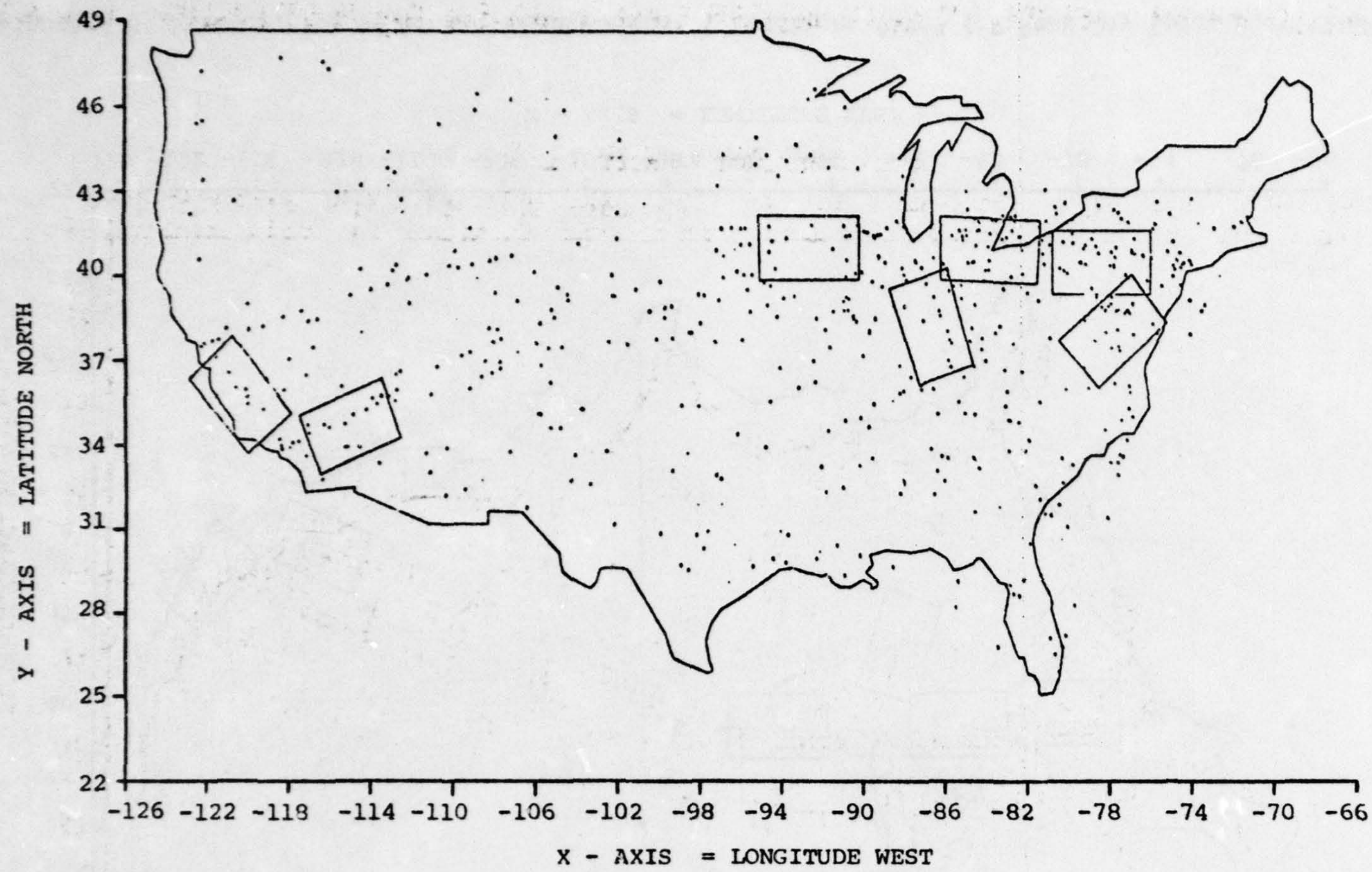

Figure A.9 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 20 GMT)

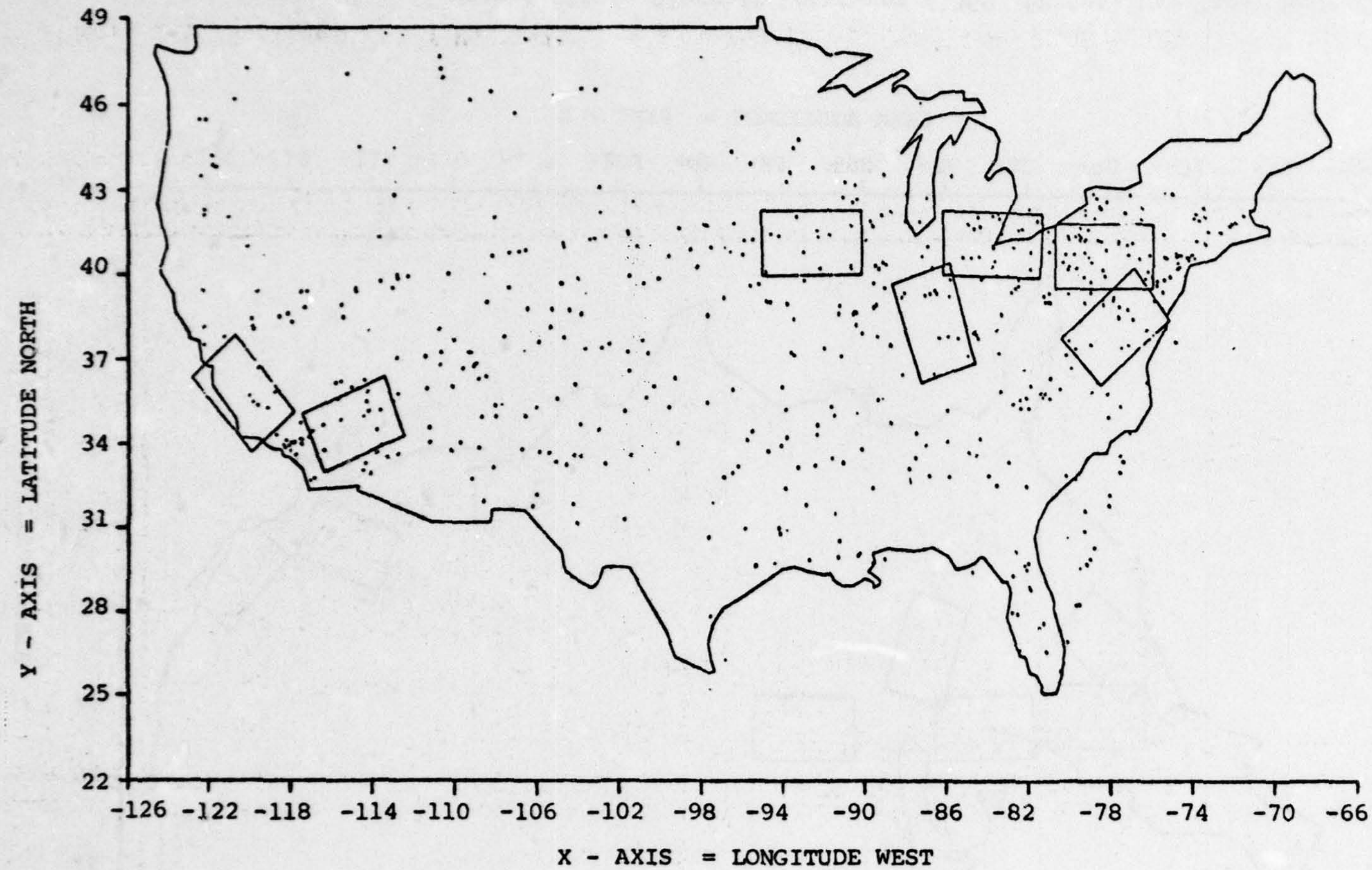

Figure A.10 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 21 GMT)

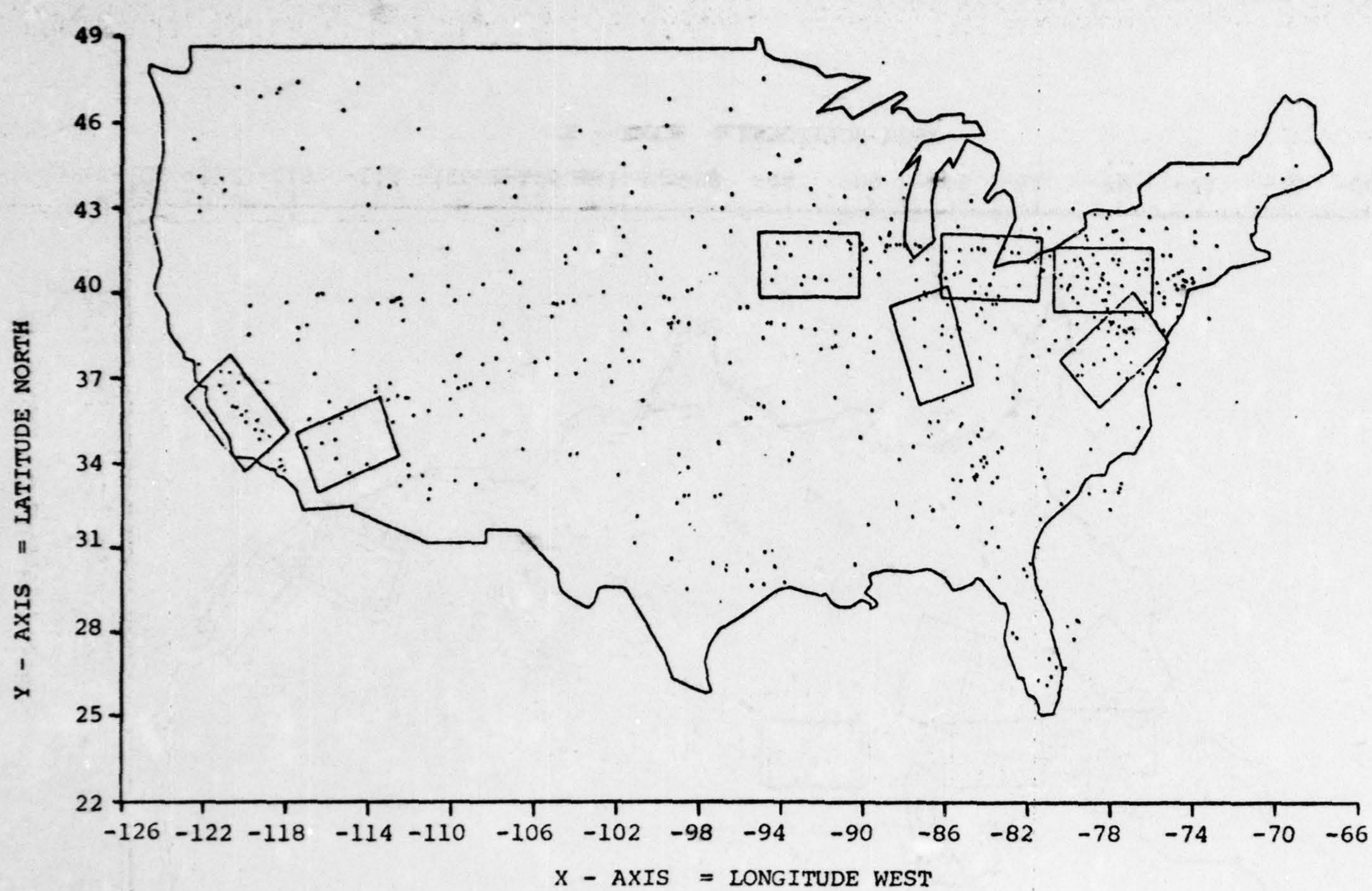

Figure A.11 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 22 GMT)

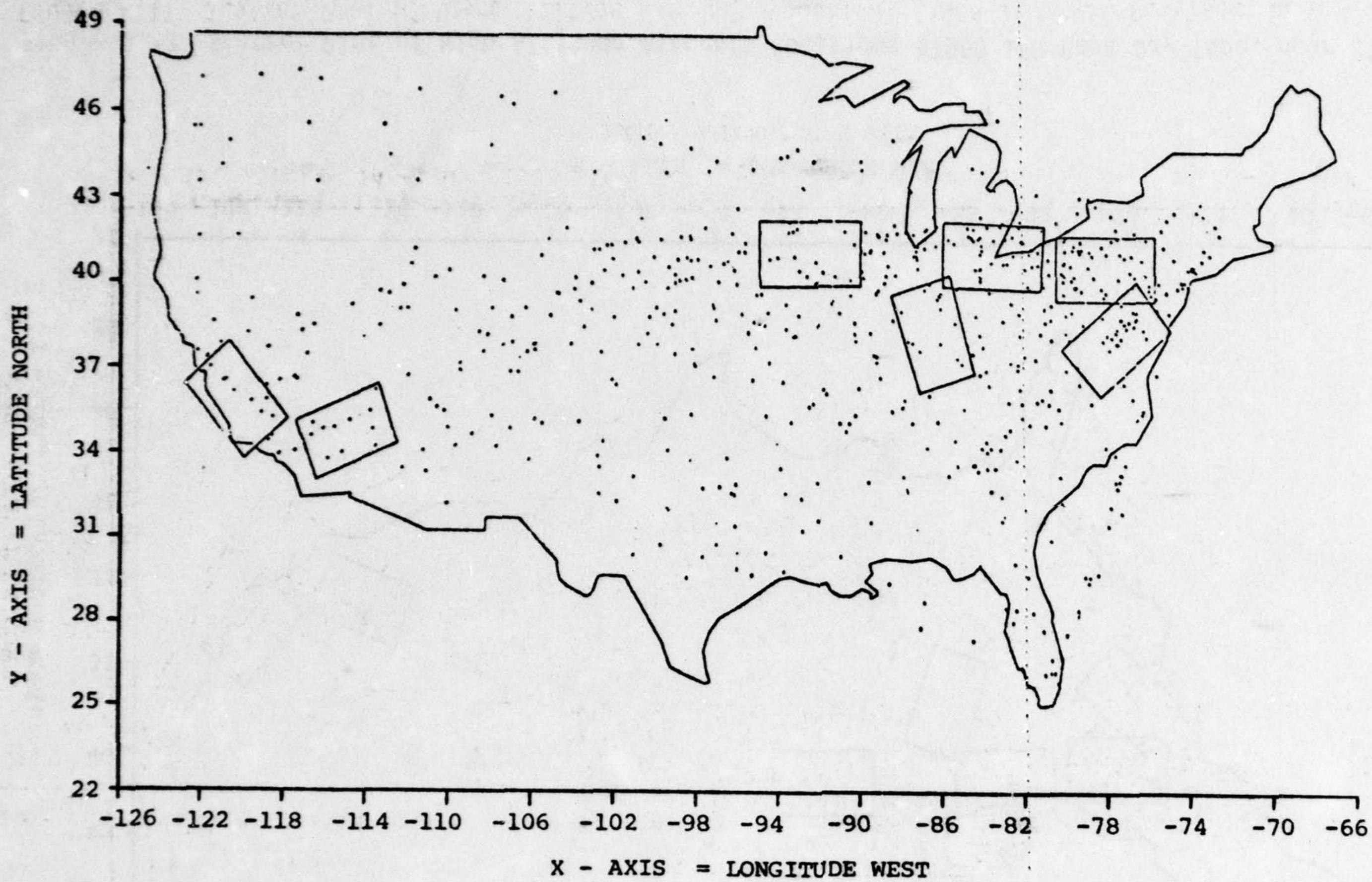

Figure A.12 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 23 GMT)

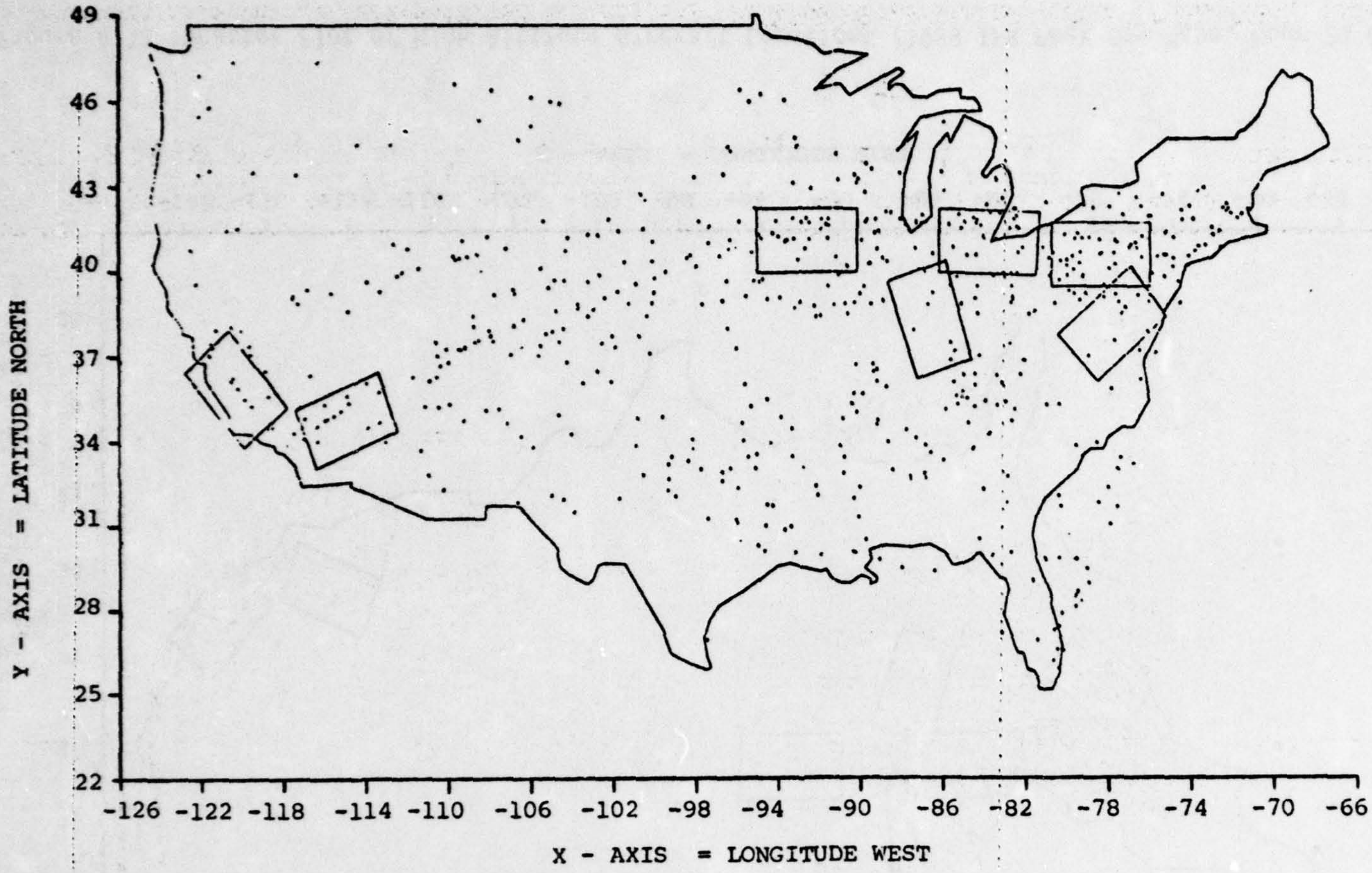

Figure A.13 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 24 GMT)

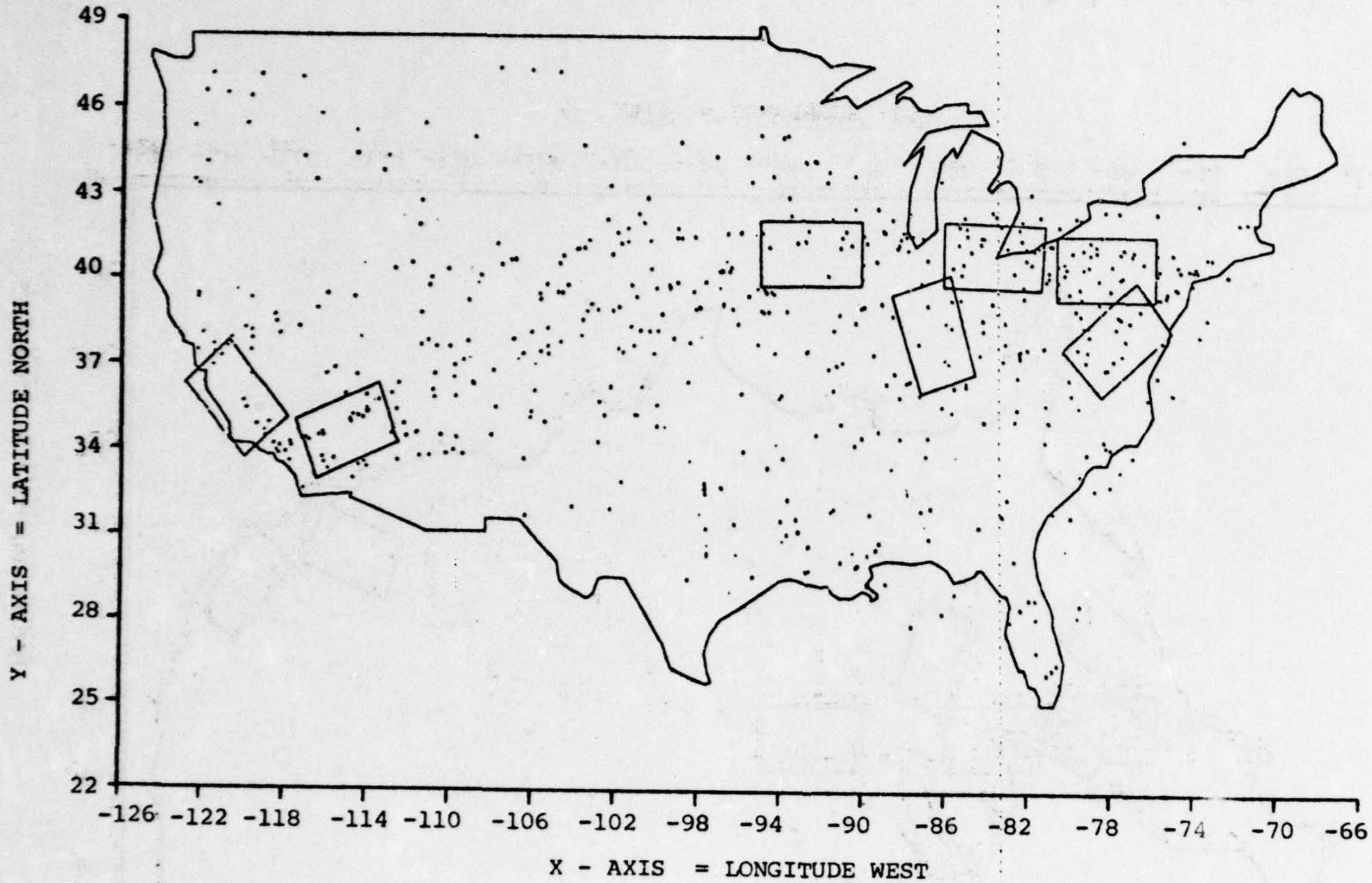

Figure A.14 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 01 GMT)

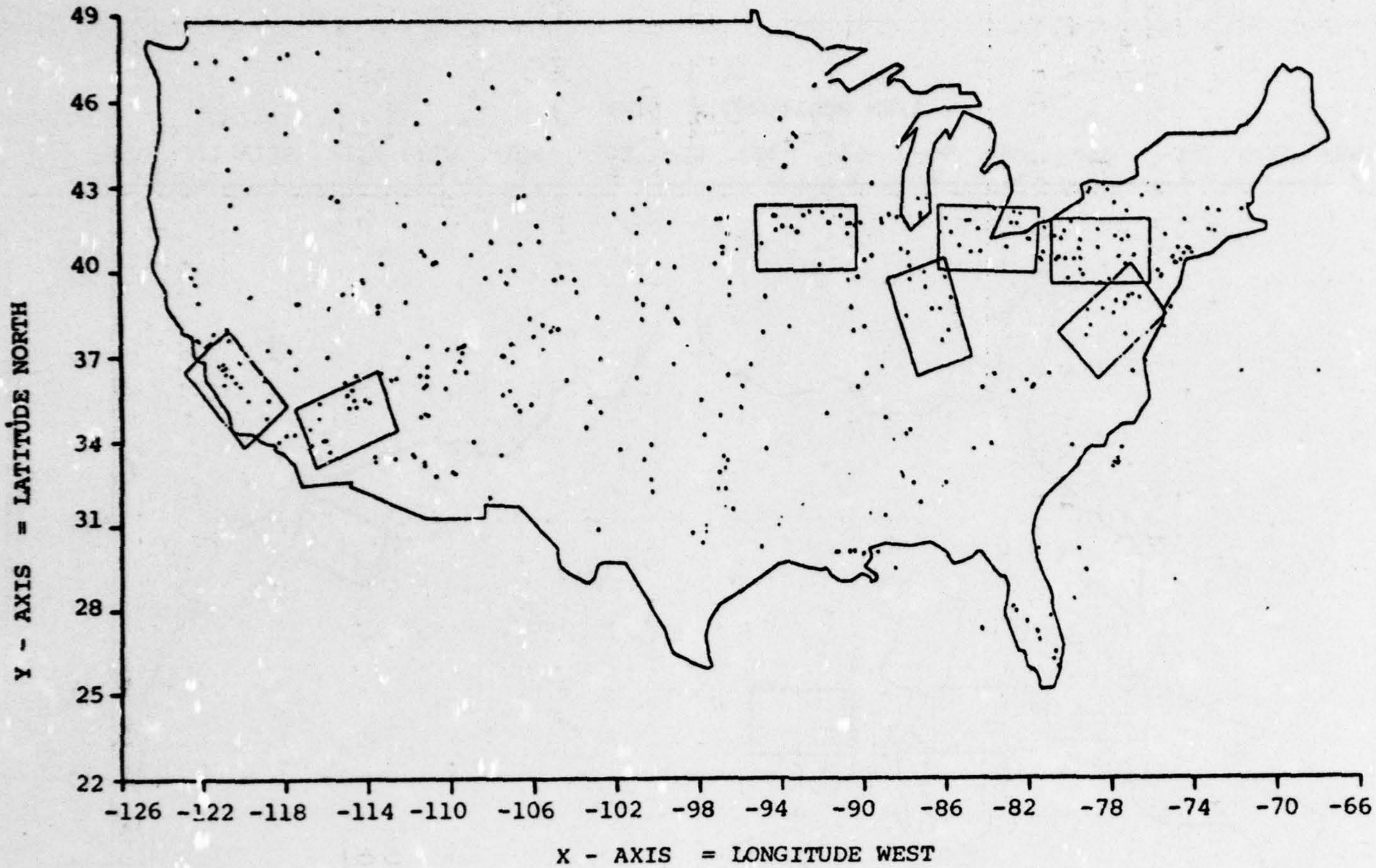

Figure A.15 Scatter Plot of High Altitude Aircraft Locations (1969 IFR Peak Day Tape, Hour 02 GMT)

APPENDIX B

DENSITY MEASURES AND RESULTS

Appendix A presents and explains the scatter plots. The next phase of the study was to utilize these plots to devise candidate enroute high density areas. For computational reasons, it was necessary to utilize pre-defined candidate areas, as a global optimization solution did not appear to be feasible. The reader will note that seven candidate areas were defined.

Experience in this area led to the somewhat preconceived notion that the candidate areas should encompass the "Golden Triangle" region, i.e., the triangle formed by New York City, Chicago and Atlanta. The plots very adequately confirmed this belief. Two areas in California were also included. These were later selected for separate studies. The area to the west of Chicago was added based upon the plot results. The area latitude-longitude boundaries are given in Table B.1. Figure B.1 shows the area plots; the degree to which these areas cover the dense regions of the country can be seen in Appendix A.

Table B.1 Candidate Busy Areas

AREA 1: WEST OF NEW YORK, 29750 nm^2 (42.00, 80.50) (42.00, 75.70) (39.70, 80.50) (39.70, 75.70)	AREA 4: SOUTH OF CHICAGO, 29489 nm^2 (39.88, 88.52) (40.62, 85.67) (36.36, 87.05) (37.08, 84.40)
AREA 2: SOUTHWEST OF NEW YORK, 29073 nm^2 (40.43, 76.62) (38.64, 74.90) (37.98, 80.19) (36.28, 78.24)	AREA 5: WEST OF CHICAGO, 30197 nm^2 (42.51, 94.94) (42.50, 90.00) (40.17, 94.89) (40.20, 90.00)
AREA 3: EAST OF CHICAGO, 29260 nm^2 (42.50, 86.00) (42.36, 81.10) (40.20, 86.00) (40.08, 81.26)	AREA 6: CALIFORNIA CORRIDOR, 28950 nm^2 (36.57, 122.88) (38.12, 120.75) (34.00, 119.95) (35.50, 117.85)
AREA 7: EAST OF LOS ANGELES, 28452 nm^2 (35.28, 117.47) (36.62, 113.43) (33.17, 116.43) (34.48, 112.46)	

*(Geodesic latitude, longitude)

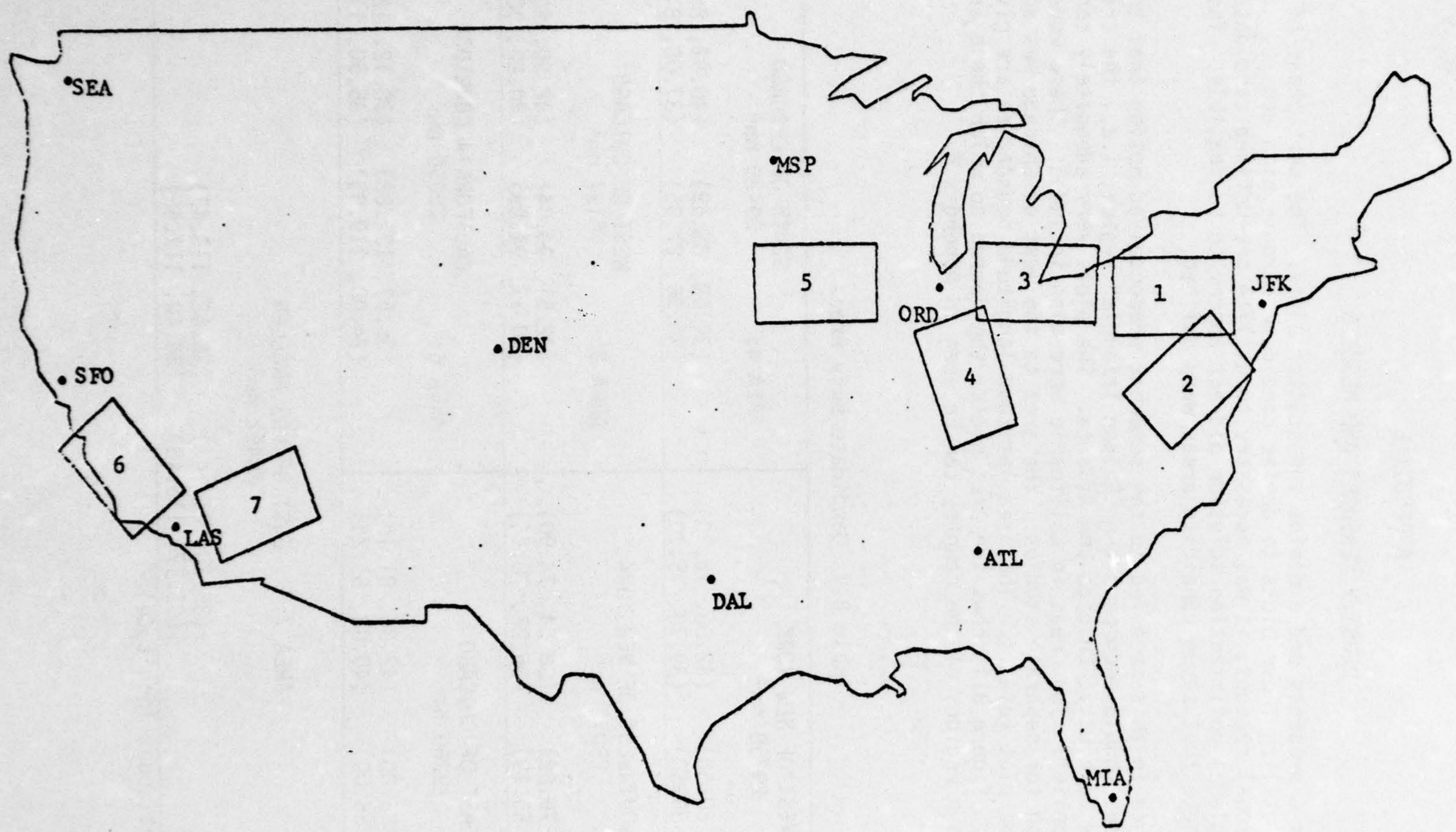

Figure B.1 Candidate Enroute High Density Areas

Four primary density/complexity measures were utilized. The first two relate directly to route structure complexity requirements; the latter two are density measures which relate primarily to area conflict rates. These are as follows:

1. Number of airport pairs going through the area (whose great circle arcs intersect the area)

2. Daily number of aircraft which enter the area (based on great circle arc)

3. Aircraft density (per square mile)

4. Aircraft density per great circle route mile

There are five variations of this last measure, the equations for which are given in Table B.2. Each of these measures involves determining the number of aircraft per mile for each great circle route containing traffic and then computing the weighted average of these statistics. The measures differ in the weights assigned. Altitude separation is considered in that each route is treated as a set of distinct paths. Measure number 2 should be viewed as the most reliable because the aircraft per mile statistics are weighted by the number of aircraft. Thus, only paths with aircraft are considered. Measures 4 and 5 are the same as 1 and 3, respectively, except for the treatment of altitude. Measures 1 and 3 divide each route with traffic into 9 altitude separated routes. Unused altitudes are treated as having zero aircraft per mile. The last two measures divide each utilized route into only those altitudes utilized in the area. Measures 4 and 5 will differ drastically from 1 and 3 when the aircraft in an area at a given time are distributed among relatively few altitude levels.

All computations were based on the 1969 IFR Peak Day Tape and were premised upon the same assumptions as the scatter plots in Appendix A. Each density measure was computed for each of the fifteen hours for which a plot was generated; i.e., 1200 to 0200 GMT (0700 to 2100 EST). Figure B.2 presents the program flow chart and Tables B.3 through B.5 summarize the results.

Table B.2 Density Measures

NOTATION: Each of the following applies to a given candidate area and a particular time.

N_{ij} = number of aircraft on great circle arc i at altitude j

n = number of great circle arcs through an area which are being utilized by at least one aircraft

M = number of altitude levels considered (maximum of 9)

m_i = number of altitude levels of arc i which have at least one aircraft

L_i = length of great circle arc i interior to the region

MEASURES:

(1)	$\sum_{i=1}^{n} \sum_{j=1}^{m} N_{ij}^2/L_i \Big/ M \sum_{i=1}^{n} L_i$	AC Per Mile Weighted by Route Miles[1]
(2)	$\sum_{i=1}^{n} \sum_{J=1}^{m} N_{ij}^2/L_i \Big/ \sum_{i=1}^{n} \sum_{j=1}^{m} N_{ij}$	AC Per Mile Weighted by the Number of AC
(3)	$\sum_{i=1}^{n} \sum_{j=1}^{m} N_{ij}/L_i \Big/ Mn$	AC Per Mile-Average of Each Path[1]
(4)	$\sum_{i=1}^{n} \sum_{j=1}^{m} N_{ij} \Big/ \max(mi) \cdot \sum_{i=1}^{n} L_i$	AC Per Mile Weighted by Utilized Route Miles[2]
(5)	$\sum_{i=1}^{n} \sum_{j=1}^{m} N_{ij}/L_i \Big/ n \cdot \max(mi)$	AC Per Mile Average of Each Utilized Path[2]

[1]For these two measures, unused altitudes are included (zero AC per mile)
[2]Unused altitudes are ignored

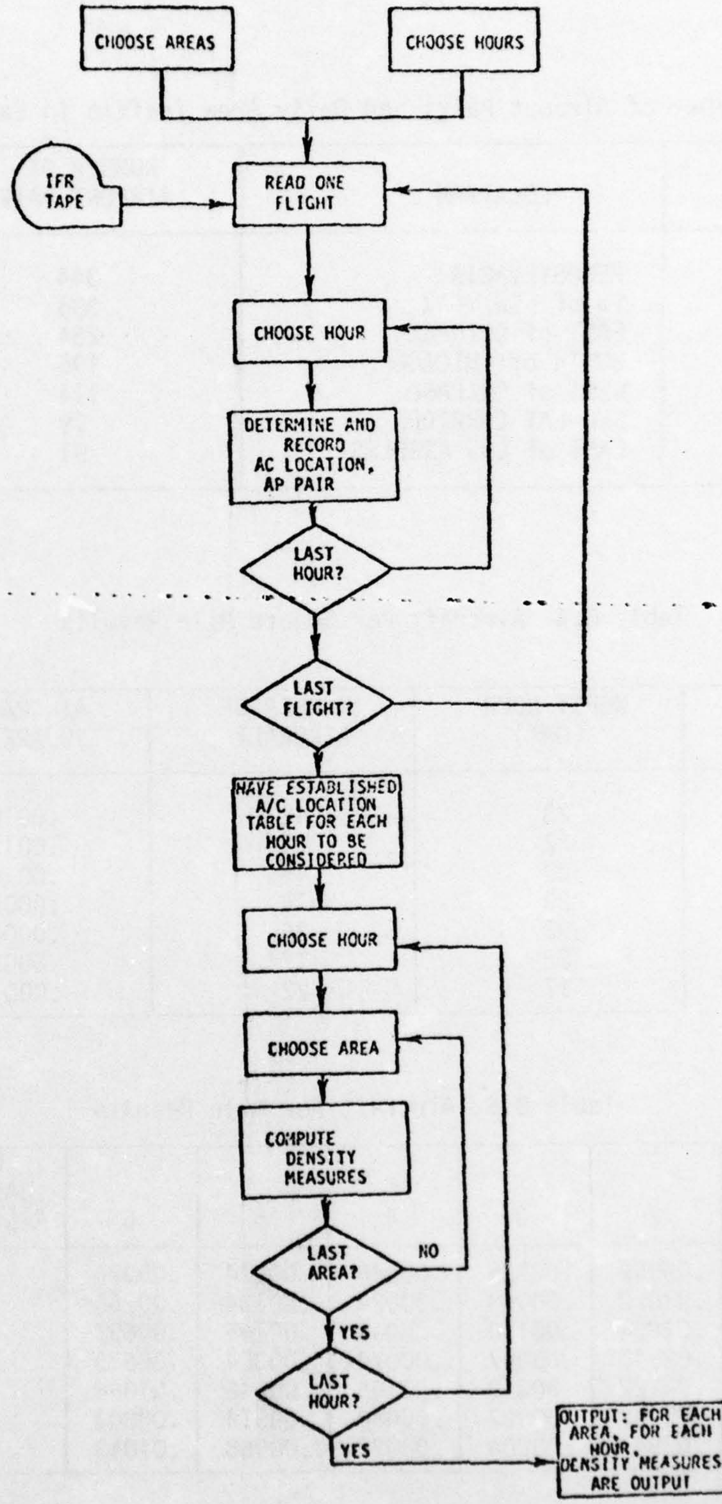

Figure B.2 Flow Chart for the Density Measure Computations

Table B.3 Number of Airport Pairs and Daily Area Traffic in Each Candidate Area

AREA	LOCATION	NUMBER OF AIRPORT PAIRS	DAILY AREA TRAFFIC
1.	PENNSYLVANIA	344	1803
2.	SW of NEW YORK	306	1309
3.	EAST of CHICAGO	284	1697
4.	SOUTH of CHICAGO	196	711
5.	WEST of CHICAGO	114	786
6.	SFO-LAX CORRIDOR	79	759
7.	EAST of LOS ANGELES	91	743

Table B.4 Aircraft Per Square Mile Results

AREA	WORST HOUR (GMT)	NUMBER OF AIRCRAFT	AIRCRAFT PER SQUARE MILE	RANK
1.	23	48	.00161	1
2.	22	35	.00120	3
3.	23	45	.00154	2
4.	23	16	.00054	7
5.	02	25	.00083	4
6.	22	17	.00059	6
7.	17	22	.00077	5

Table B.5 Aircraft Per Mile Results

AREA	1	2	3	4	5	6	RANK BASED ON AVG. VALUE	RANK (MEASURED 2)
1	.00062	.04062	.00188	.00046	.00274	.00926	3	2
2	.00025	.01022	.00053	.00024	.00134	.00252	7	7
3	.00054	.02894	.00130	.00040	.00165	.00657	5	4
4	.00046	.02547	.00097	.00070	.00304	.00613	6	5
5	.00087	.04122	.00210	.00165	.00646	.01046	2	1
6	.00057	.02449	.00927	.00068	.00514	.00803	4	6
7	.00075	.03941	.00204	.00075	.00968	.01053	1	3

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AREA NAVIGATION ROUTE WIDTH REQUIREMENTS. (U)
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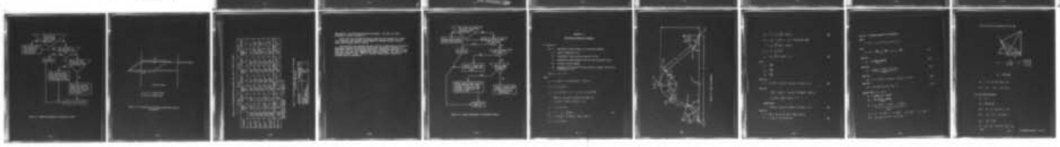

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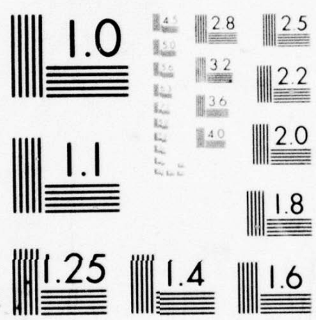


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

APPENDIX C

PARALLEL ROUTE CAPACITY ESTIMATION

A methodology by which to estimate the capacity of a system of a parallel routes was developed. The methodology was applied to determine the impact of route width on the traffic entering and leaving the Los Angeles area from the east. The eastern approach to Los Angeles is bounded to the north and south by military restricted areas. The number of routes which can pass between these areas is a direct function of the route width. If the route width is ±6 nm, for example, only two routes can be accommodated. The capacity of these two routes must certainly be less than that of the five routes which could be made available by utilizing a route width of ±2.5 miles. The purpose of the capacity estimation study is to determine the benefit which can be gained by this reduction in route width.

The methodology adopted is composed of the fast time simulation of traffic on a set of parallel routes. The objective is to quantify the time and fuel penalties which are incurred by the aircraft due to the occurrence and resolution of overtake conflicts. The controller workload required for the resolution of the conflicts is also estimated as a measure of impact to the ATC system.

A computer program was developed to perform the simulation. In order that the simulation results appropriately reflect the area being studied, four basic program inputs were defined: the route structure model, the traffic sample, controller conflict resolution logic and the conflict penalty logic. The purpose of this appendix is to explain how these inputs were derived.

C.1 ROUTE STRUCTURE

For this application, a set of parallel enroute routes was used. The length of the structure was chosen to be 50 nautical miles. This route length corresponds to the distance over which restricted areas east of Los Angeles actually force routes together. One situation of special interest concerning the structure lies outside of the scope of this study. The region being simulated is adjacent to the transition area of Los Angeles. Delays which are imposed in the simulated area will be intensified in the transition area. It was not possible to include the three dimensional aspects of the transition route structure.

Three route structures were simulated, each corresponding to a different route width. The distance between the restricted areas is 25 nm. Thus, for route widths of ±2.5, ±3.0, and ±4 miles, the structures were composed of 5, 4 and 3 parallel routes respectively.

C.2 TRAFFIC DATA

The aircraft overtake conflict rates over a system of parallel routes will be significantly influenced by the aircraft speeds and altitudes. As a consequence, the results will vary when applied to different areas of the country. Since the simulation was to relate to the eastern approach to Los Angeles, the aircraft data was obtained for this region.

The simulation utilizes hourly aircraft flow rates as the data base from which to randomly generate flights. The use of hourly flow rates corresponding to the "worst" hour was desired, but an assumption had to be made as to how this hour was to be determined. The worst hour, based upon the performance measures being computed (time and fuel penalties) is a function of the aircraft mix as well as total number of aircraft. However, if this aspect were to be considered, then determination of which hour is worst would have entailed simulating each hour. As an alternative, the hour was chosen based upon the hourly maximum total aircraft which enter and leave the area.

The FAA traffic forecast for 1982 was used [2]. It was first necessary to determine which flights (or airport pairs) would ordinarily demand airspace between the two restricted areas of interest. Figure C.1 shows the resulting region. Lines were drawn from LAX through the centers of each restricted area. All traffic to or from the Los Angeles area (including Burbank, Ontario and Santa Ana) whose direction of travel fell within this region were considered. Traffic either north or south of this region would be expected to go to the outside of the restricted areas. This region was divided into ten zones as shown in Figure C.1. The traffic data (flow rates) were then tabulated by zone, altitude and aircraft type. The aircraft type definitions are given in Table C.1. Only aircraft types 8-11 and 13-20 were considered, as no other performance data was available. Of those left out, however, all are propeller driven aircraft or high performance military jets.

The following assumptions were made in processing the flights on the traffic tape. These are essentially the same as those used in other parts of this study. Specifically, great circle flight paths were used to determine the direction from which aircraft enter the area. The corresponding flight distances, in conjunction with the requested true air speed (a data item on the traffic tape) was used to determine the arrival times at the area boundary.

The traffic tape was processed first to determine the hour when the traffic was a maximum. Table C.2 shows the results of this process.

Having chosen the hour from 5 to 6 pm PST as the peak hour, the tape was again processed to determine for each zone, how many aircraft of each type, from each direction (to or away from Los Angeles) and at each altitude desire to traverse the area.

The expected or mean number of aircraft are approximated by the hourly flow rates and an exponential distribution of interarrival times is assumed. Subsequent to determining the flow rates, higher or lower traffic levels were obtained by multiplying all flow rates by the appropriate constants.

The aircraft were assigned to individual routes based upon certain assumptions about the route design. If 'n' parallel routes exist through the area, it is expected that the northern most route was designed to serve the northernmost n^{th} of the traffic, etc. This will not result in the shortest routes in all cases, but the procedure is consistent with current design practice. Route assignments are made based on this rule, with two exceptions. A correspondence between the 10 zones and routes was established so that the traffic on each route

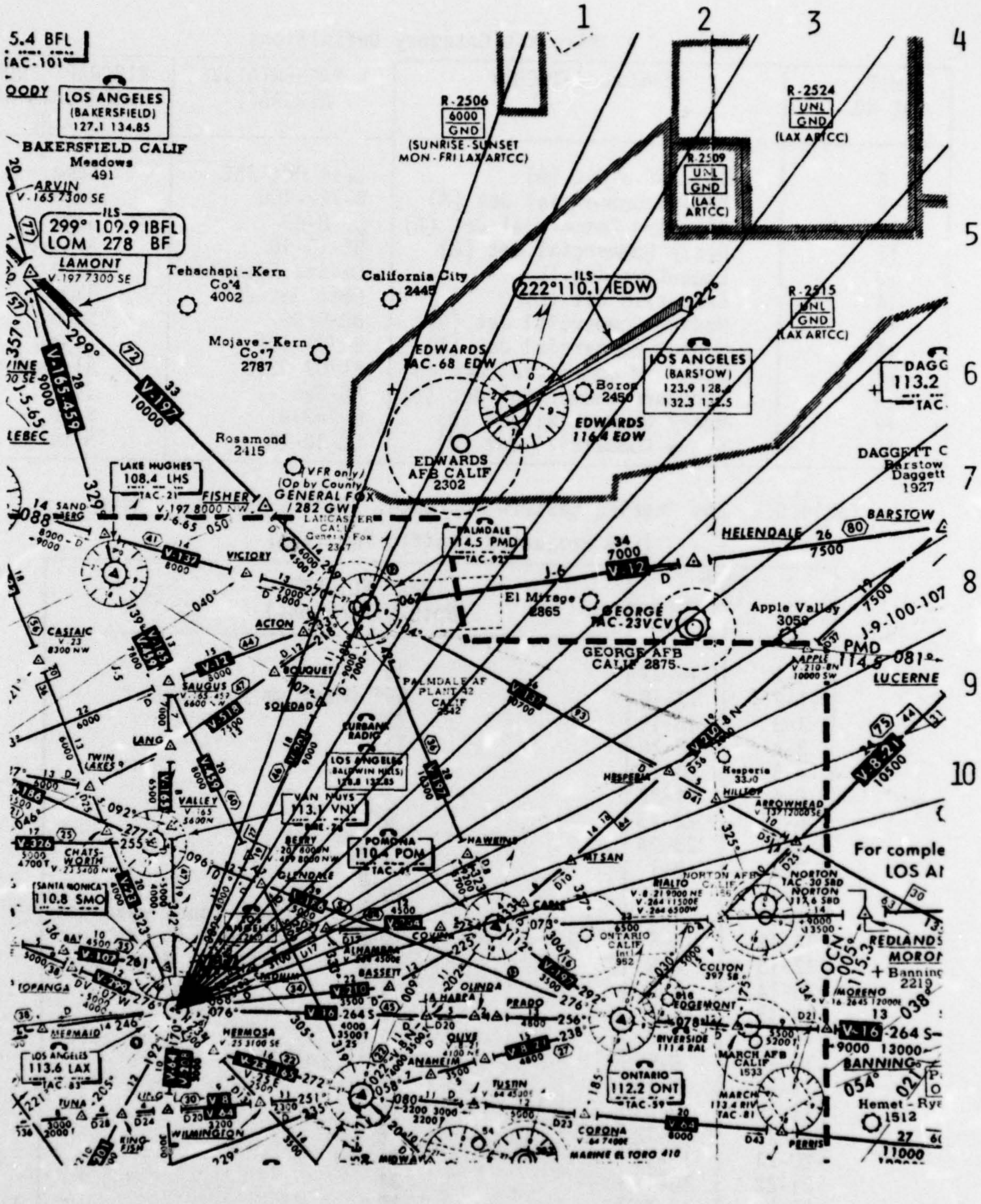


Figure C.1 Eastern Approach to Los Angeles

Table C.1 Aircraft Category Definitions

MIT AC NO.	GENERAL CATEGORY	REPRESENTATIVE AIRCRAFT	AIRCRAFT FROM WHICH DATA WAS OBTAINED
8	Executive Jet (A)	Lear Jet 25C	Same
9	Medium Commercial Jet (A)	B-727-100	Same
10	Standard Commercial Jet (A)	DC-8-63	Same
11	Heavy Commercial Jet (A)	DC-10-10	Altered 747
13	Executive Jet (B)	Cessna Citation	Same
14	Executive Jet (C)	Lear Jet 25C	Same
15	Medium Commercial Jet (B)	DC-9-30	Same
16	Medium Commercial Jet (C)	B-727-100	Same
17	Standard Commercial Jet (B)	B-707-320C	Altered DC-8
18	Standard Commercial Jet (C)	DC-8-63	Same
19	Heavy Commercial Jet (B)	B-747-B	Same
20	Heavy Commercial Jet (C)	DC-10-10	Altered 747

Table C.2 Los Angeles Eastern Approach: Traffic Totals by Hour

(FAA Projected Traffic for 1982)

HOUR		TOTAL FLIGHTS (Both Directions)
GMT	PST	
0-1	16-17	36
1-2	17-18	50* (Maximum Traffic)
2-3	18-19	28
3-4	19-20	11
4-5	20-21	4
5-6	21-22	3
6-7	22-23	0
7-8	23-24	0
8-9	0-1	0
9-10	1-2	0
10-11	2-3	0 These hours were not included in the traffic projection.
11-12	3-4	0
12-13	4-5	0
13-14	5-6	0
14-15	6-7	0
15-16	7-8	0
16-17	8-9	5
17-18	9-10	20
18-19	10-11	8
19-20	11-12	7
20-21	12-13	31
21-22	13-14	34
22-23	14-15	29
23-24	15-16	36

is as equal as possible, but traffic in a given zone was not subdivided, except when absolutely necessary. Further, the simulation was designed to record penalties due to conflicts which begin in the area. Thus, aircraft cannot be allowed to be in conflict when they enter the area. Conflicts of this type are assumed to have been previously resolved. The logic used to reflect this conflict resolution is similar to that used to resolve conflicts which begin in the area.

C.3 CONTROLLER RESOLUTION LOGIC

Controller conflict resolution logic was developed as a part of the RNAV economic benefits analysis [3] based upon the controller experiments conducted at MIT. While the controller logic developed was somewhat complex, its application in this simulation is far simpler in light of the fact that only overtake conflicts can occur. Figure C.2 depicts the overtake resolution logic.

For application in this study, several refinements are appropriate. The set of possible resolution techniques is given as follows:

1. Speed reduction to the faster aircraft
2. Parallel offset
   a. To left or right
   b. To faster or slower aircraft
3. Altitude reclearance for the faster aircraft to lower altitude

The manner in which these resolution techniques are used is, of course, a program variable. Every effort was made to tailor the logic to the particular area being studied. This resulted in three sets of resolution logic; one for west bound flights, one for eastbound flights and a "pre-simulation" logic.

C.3.1 Pre-Simulation Logic

The pre-simulation logic is critical to the validity of the simulation results. The intent of the simulation was to assess the penalties which result from traversing the 50 mile structure.

The random generation of arrival times can result in cases where an aircraft is in conflict at the time that it enters the structure. In reality, these conflights would have been previously resolved and the simulation must properly account for this.

That this is not a straightforward procedure is illustrated by the following example. Suppose that every time two aircraft enter an area in conflict, the second aircraft is simply delayed so as to provide the required separation. One would expect that in half of these cases, the second aircraft would be the faster of the two and would therefore come into conflict again later in the simulation. In each case, this logic would result in an erroneous simulation conflict. A great many conflicts would be resolved in the simulated area which in reality would not have taken place.

While the controller logic inherent in this simulation cannot be referred to as "optimum", an effort has been made to utilize efficient logic. Whenever

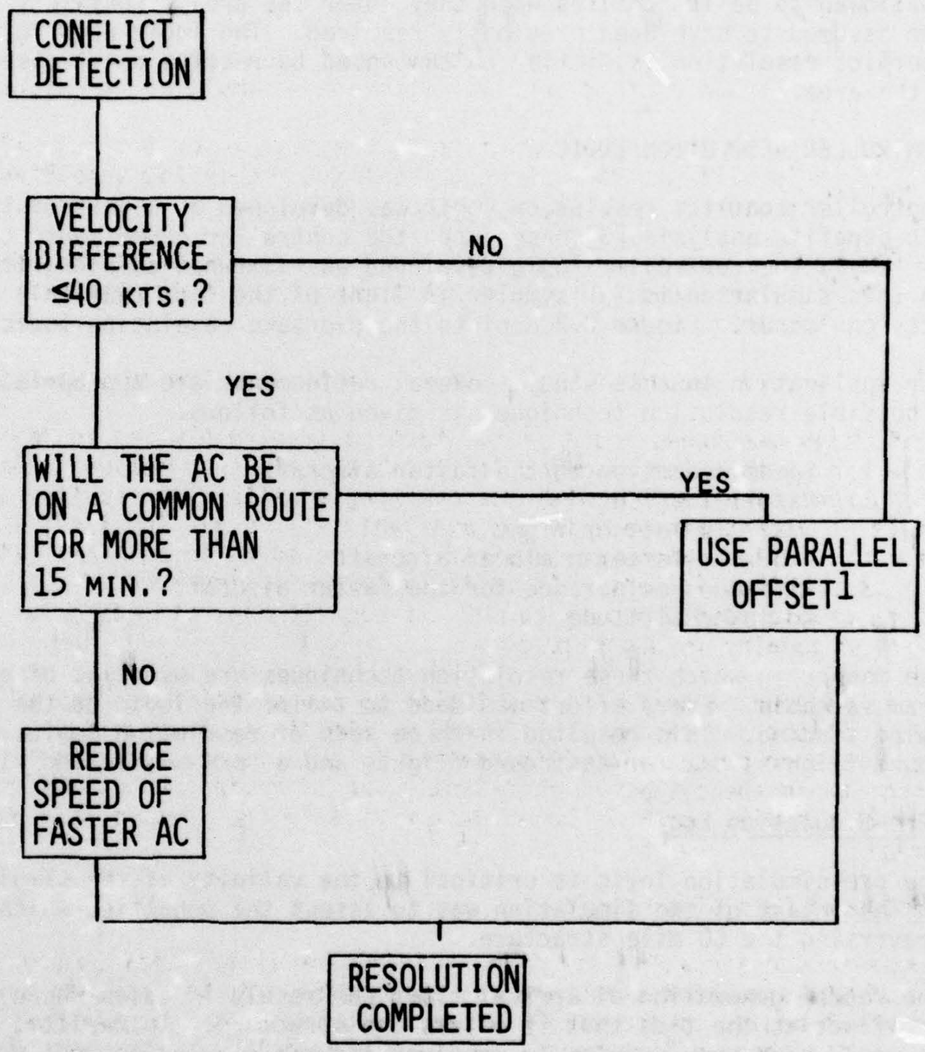


Figure C.2 Level Overtake Resolution Logic (RNAV)

a conflict is detected in the simulation, the highest priority resolution technique whose constraints are satisfied is utilized. The pre-simulation resolution priority system is listed as follows:

1. Offset the second aircraft to an adjacent route if this will not cause another conflict within the simulated structure.
2. Reclear the second aircraft to the next lower altitude if this will not cause another conflict within the simulated structure.
3. Do 1 or 2 of the above which delays any new conflict the maximum amount, providing that the aircraft do not enter the area in conflict.
4. Reduce second aircraft speed to achieve a 5 mile separation.

Not specifically mentioned above is the fact that no resolution is made without first determining that the maneuver is feasible. Altitude reclearances cannot be made if transition headons with the opposing traffic will result. No maneuver can be made if vacant airspace is not available at the new (desired) location. During the simulation, whenever an aircraft is moved to an adjacent route, a record of this action is kept. If it is subsequently involved in a conflict, the most favorable resolution is to move it back to its desired route; an action with which no penalty is associated.

As can be seen, a permanent resolution to the conflict is desired and achieved in almost all cases. This logic is applied to each aircraft as it enters the area. Whether or not a conflict exists is determined by considering only those aircraft in the system at that time. The determination of whether or not future conflicts will occur is based on aircraft in the area as well as those yet to enter.

C.3.2 Westbound Resolution Logic

For westbound aircraft, the effect of the transition area immediately to the west of the simulated structure was considered. It was assumed that any conflict which begins in the simulated area should be permanently resolved when possible; i.e., the conflict should not simply be delayed. The use of an offset or altitude reclearance may resolve the immediate conflict, but these techniques were avoided if the conflict would have reoccurred subsequently.

These objectives impose relatively severe constraints on the available resolution techniques. They are considered to be realistic, however, for an area bordering on the transition into a major terminal. The resolution priority system is given below.

1. Offset either aircraft if this involves returning to its desired route.
2. Reclear the faster aircraft to the next lower altitude and reduce the speed of the slower aircraft so that a transition conflict will not occur, providing that the speed reduction is of lesser magnitude than in item 3.

3. Reduce the speed of the faster aircraft to equal that of the slower.

The reader will note that an offset to the slower aircraft, normally a common maneuver, was seldom used for arrivals. The rationale is that the impact to the slower aircraft is always less when the faster aircraft is sent to a lower altitude, even when the slower aircraft must endure a speed reduction. For an arrival aircraft, being recleared to a lower altitude involves a time benefit and only a minimal fuel penalty. Thus, this logic did not appear to give undue advantage to the slower aircraft.

C.3.3 Eastbound Resolution Logic

For departures from the Los Angeles area, several of the previous constraints were eliminated and more resolution techniques were found to provide viable solutions.

The assumption that conflicts be permanently resolved, while still adhered to, had far less significance. Offsets and altitude reclearances could be assumed to remain in effect as long as was necessary to resolve the conflict. Conversely, speed reductions were considered so costly as to be used only as a last resort and then as a temporary measure. The following priority system resulted, subject again to the availability constraints previously mentioned.

1. Offset either aircraft if this involves returning to its desired route.

2. Offset the slower aircraft.

3. Offset the faster aircraft.

4. Reclear the faster aircraft to the next lower altitude.

5. Reduce the speed of the faster aircraft until one of the above techniques becomes available.

The determination of the direction to which offsets are flown is based upon delaying future conflicts to the maximum extent.

C.4 CONFLICT PENALTY ASSESSMENT

The last major part of the simulation is the assessment of penalties. For several reasons, this was not performed by simply recording the time or fuel used in the system relative to an optimum. The objective was to assess penalties which are caused by the simulated structure, not necessarily penalties incurred within the structure. The penalty associated with an offset is composed of two parts; the distance (time and fuel) lost while travelling to the offset and the distance lost while returning. In a structure of length 50 miles, the second maneuver will never be witnessed, but this does not justify assessment of half the penalty. The same is true of altitude reclearances. Other complications must also be considered. When an aircraft enters the structure on a non-desired

route (offset), no penalty should be assessed if it is forced to remain there, nor should there be a penalty (or benefit) if it can be returned to the desired route. In general, no penalties are associated with pre-simulation resolution. Speed reductions are considered last resort and temporary measures. A speed reduction results from the current traffic environment and penalties are therefore associated with the time duration of the reduction witnessed in the simulation.

The penalty logic has been devised so that the penalties are assigned to each aircraft as the resolution techniques are employed. During the simulated flight of each aircraft, the following information is maintained:

1. aircraft type
2. current and desired route
3. current altitude
4. current speed
5. total time and fuel penalties

All penalty computations are based upon the data given in Tables C.3 through C.6. These tables were generated as a part of the RNAV benefits payoff study [3]. The performance data for six aircraft types were analyzed. Since 12 aircraft categories were used in the simulation, data for the remaining 6 types was extrapolated from the tables.

The category definitions and bases for the extrapolations are given in Table C.2. The subcategories, denoted by A, B and C, reflect medium, low and high performance subdivisions of the primary categories. For the purpose of penalty computation, the DC-10 was assumed to have an equal speed profile and two thirds of the fuel consumption of the 747. Boeing 707 penalties were obtained from the DC-8-63 penalty tables by multiplying by .97 and .92 for time and fuel respectively.

Figure C.3 presents the penalty assessment logic for conflicts between westbound flights. The entire penalty for an altitude reclearance is assigned at the time the maneuver is made, while the penalties for speed reductions are computed for each simulation time interval.

The derivation of the altitude reclearance penalty is shown in Figure C.4. The penalty is obtained from Table C.6 by comparing the time and fuel required for travel of X miles at each of the two altitudes. This assumes that the transition area (beginning of descent) occurs immediately at the end of the simulated area. The actual repositioning of the aircraft is based on Table C.5. This table provides the time and distance necessary to traverse from a given altitude to 18,000 feet. Differences between the table values for two different initial altitudes therefore provides the time and distance to descend from one altitude to the other.

The speed adjustment penalty is based on Table C.4 which was developed solely for this purpose.

The primary difference in penalty assessment for eastbound aircraft is that the altitude reclearance maneuver is assumed to include the climb back to the desired altitude and the duration of the flight at the lower altitude is based upon the speed difference between the aircraft rather than the area bounds.

Table C.3 Aircraft Speed and Fuel Consumption by Altitude

AC TYPES

		DC-8		DC-9		B 727		B 747		Cessna Citation		Lear Jet	
	Altitude	TAS	lbs/nm	TAS	lbs/nm	TAS	lbs/nm	TAS	lbs/nm	TAS	lbs/nm	TAS	lbs/nm
1.	18000	432	35.62	415	18.73	432	20.97	496	61.33	337	4.20	382	5.02
2.	19000	438	34.41	419	17.25	438	20.76	504	62.78	340	4.11	389	4.97
3.	20000	444	33.03	423	15.77	444	20.55	512	64.23	343	4.02	396	4.92
4.	21000	451	32.51	430	15.56	451	20.18	511	62.75	343	3.94	403	4.87
5.	22000	457	31.99	437	15.35	457	19.80	510	61.27	344	3.81	410	4.82
6.	23000	463	31.85	443	15.15	463	19.64	508	60.75	345	3.68	417	4.77
7.	24000	470	31.70	441	14.93	470	19.27	506	57.94	345	3.55	424	4.72
8.	25000	477	31.32	439	14.71	477	19.16	504	55.80	346	3.44	431	4.67
9.	26000	478	30.61	437	14.26	478	18.32	502	54.11	347	3.32	438	4.62
10.	27000	476	29.41	436	13.88	476	17.99	500	52.71	348	3.20	445	4.57
11.	28000	474	28.87	434	13.50	474	17.42	497	51.41	349	3.08	451	4.53
12.	29000	472	28.21	431	13.19	472	17.01	495	50.23	349	3.07	457	4.46
13.	31000	468	27.49	428	12.69	468	16.56	491	48.10	348	2.88	452	4.13
14.	33000	464	26.46	424	12.24	464	16.05	486	46.47	346	2.69	448	3.79
15.	35000	460	26.19	420	11.79	460	15.34	482	46.33	344	2.52	445	3.62
16.	37000	457	27.04	416	11.34	456	14.63	480	46.19	342	2.35	441	3.44
17.	39000	457	27.89	412	10.89	452	13.92	480	47.62	340	2.18	441	3.29
18.	41000	457	27.89	403	10.44	448	13.21	480	47.62	338	1.99	441	3.21

Table C.4 Speed Reduction Time and Fuel Penalties (per hour of reduction)

DC-8-63 M 0 .80

NOMINAL ALTITUDE

	FL 390		FL 350		FL 310		FL 270	
OVERTAKE RATE (knots)	TIME (min) per HOUR	FUEL (lb) per HOUR	TIME (min) per HOUR	FUEL (lb) per HOUR	TIME (min) per HOUR	FUEL (lb) per HOUR	TIME (min) per HOUR	FUEL (lb) per HOUR
10	1.31	120	1.30	135	1.28	155	—	—
20	2.62	153	2.60	203	2.56	272	—	—
30	3.93	123	3.91	198	3.84	309	—	—
40	5.23	46	5.21	124	5.12	290	—	—

Values for Weight Appropriate for Each Altitude

Linear interpolation is used for overtake rates or altitudes in between those given. For overtake rates less than 10 knots: interpolation is performed linearly to zero penalty at zero knots. For overtake rates greater than 40 knots and for altitudes outside of those given, linear extrapolation is used.

SPEED ADJUSTMENT
PENALTY VALUES ARE PER HOUR OF RESTRICTION

DC-9-30

	FL 390		FL 350		FL 310		FL 270	
OVERTAKE RATE (knots)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)
10	—	—	1.35	43	1.33	91	1.31	110
20	—	—	2.70	57	2.66	149	2.61	178
30	—	—	4.05	51	3.98	171	3.91	234
40	—	—	5.41	42	5.31	185	5.22	267

SPEED ADJUSTMENT
PENALTY VALUES ARE PER HOUR OF RESTRICTION

B-747

	FL 390		FL 350		FL 310		FL 270	
OVERTAKE RATE (knots)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)
10	1.24	-35	1.24	178	1.22	292	—	—
20	2.49	-224	2.48	241	2.43	472	—	—
30	3.73	-627	3.72	180	3.65	564	—	—
40	4.98	-1175	4.96	-37	4.87	639	—	—

SPEED ADJUSTMENT
PENALTY VALUES ARE PER HOUR OF RESTRICTION

B-727

	FL 390		FL 350		FL 310		FL 270	
OVERTAKE RATE (knots)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)
10	—	—	1.30	90	1.28	179	1.26	-35
20	—	—	2.60	133	2.56	169	2.51	+63
30	—	—	3.91	137	3.84	196	3.77	127
40	—	—	5.21	118	5.12	274	5.02	177

SPEED ADJUSTMENT
PENALTY VALUES ARE PER HOUR OF RESTRICTION

Lear Jet 24B/25C

	FL 450		FL 410		FL 370		FL 330	
OVERTAKE RATE (knots)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)
10	1.36	27	1.36	17	1.36	20	1.34	26
20	2.72	52	2.72	32	2.72	38	2.68	49
30	4.08	75	4.08	46	4.08	57	4.02	71
40	5.44	95	5.44	94	5.44	73	5.36	91

SPEED ADJUSTMENT
PENALTY VALUES ARE PER HOUR OF RESTRICTION

Cessna Citation

	FL 390		FL 350		FL 310		FL 270	
OVERTAKE RATE (knots)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)	TIME (min)	FUEL (lb)
10	—	—	1.74	21	1.72	30	1.71	32
20	—	—	3.49	39	3.45	56	3.43	63
30	—	—	5.23	56	5.17	75	5.14	91
40	—	—	6.98	64	6.90	88	6.86	110

Table C.5

Descent time, distance and fuel from cruise altitude to 18,000 feet

DC-8-63, 250K lbs.

FLIGHT LEVEL	TIME (min)	DISTANCE (nm)	FUEL (lb)
34,000	5.748	48.6	306.4
32,000	5.070	43.1	266.9
30,000	4,440	37.6	235.4
28,000	3.780	32.2	205.4
26,000	3.180	26.6	168.4
24,000	2.340	19.2	122.4
22,000	1.572	12.7	81.8
20,000	0.780	5.8	39.4

DC-9-30, 199K lbs.

FLIGHT LEVEL	TIME (min)	DISTANCE (nm)	FUEL (lb)
30,000	10,134	78.16	778.0
28,000	7.104	54.26	481.0
26,000	3.864	29.06	188.0
24,000	1.944	13.26	29.0
22,000	1.284	9.06	16.7
20,000	0.624	4.36	10.0

B-727, 150K lbs.

FLIGHT LEVEL	TIME (min)	DISTANCE (nm)	FUEL (lb)
30,000	2.58	20.7	80
28,000	2.16	17.1	70
26,000	1.74	13.9	55
24,000	1.32	10.5	50
22,000	0.90	7.1	30
20,000	0.42	4.0	20

B-747, 600K lbs.

FLIGHT LEVEL	TIME (min)	DISTANCE (nm)	FUEL (lb)
34,000	5.34	41.0	270
32,000	4.56	35.5	230
30,000	3.90	30.5	195
28,000	3.18	25.1	155
26,000	2.76	21.0	140
24,000	2.04	16.4	110
22,000	1.68	12.1	90
20,000	0.84	5.4	40

Cessna Citation Model 500, 9.5k lbs.

FLIGHT LEVEL	TIME (min)	DISTANCE (nm)	FUEL (lb)
30,000	4.00	25.5	49.5
28,000	3.35	21.0	43.0
26,000	2.65	16.5	35.5
24,000	2.00	12.0	27.0
22,000	1.35	8.0	18.0
20,000	0.65	4.0	9.0

Lear Jet, 12.5 lbs.

FLIGHT LEVEL	TIME (min)	DISTANCE (nm)	FUEL (lb)
40,000	7.3	53	139
38,000	6.7	48	129
36,000	6.0	43	118
34,000	5.3	38	107
32,000	4.7	33	95
30,000	4.0	28	82
28,000	3.3	23	70
26,000	2.7	19	57
24,000	2.0	14	43
22,000	1.3	9	29
20,000	0.7	5	14

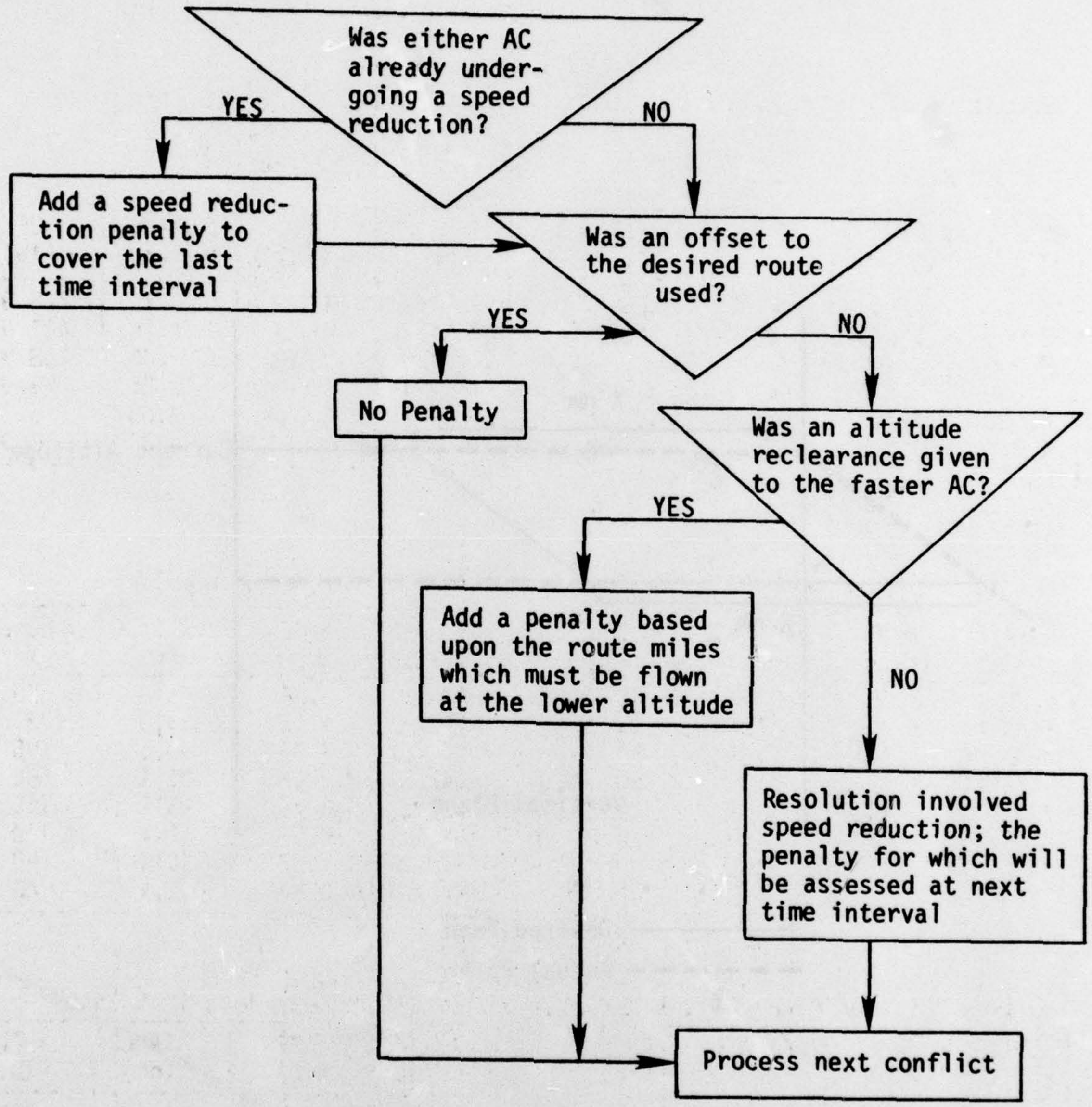


Figure C.3 Penalty Assessment for Westbound Flights

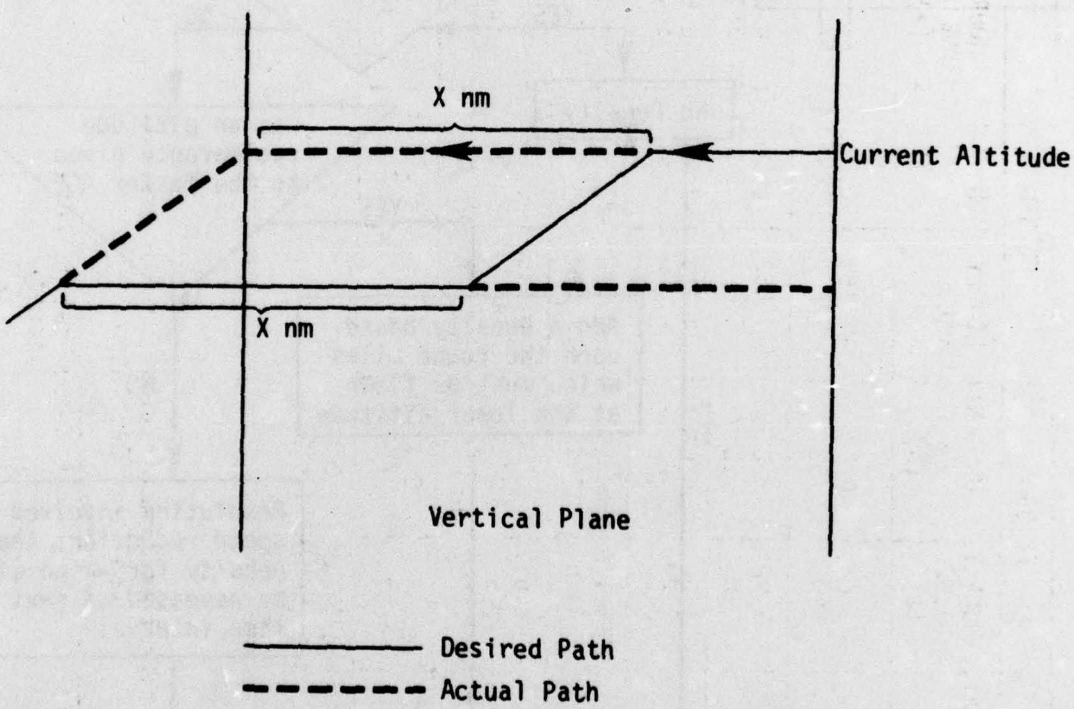


Figure C.4 Illustration of Altitude Reclearance Penalty
(Westbound)

Table C.6 Altitude Reclearance Penalty (per hour at lower altitude)

AIRCRAFT		FL 390 HOURLY VALUE (a)	FL 390 CONSTANT (b)	FL 350 HOURLY VALUE (a)	FL 350 CONSTANT (b)	FL 310 HOURLY VALUE (a)	FL 310 CONSTANT (b)	FL 270 HOURLY VALUE (a)	FL 270 CONSTANT (b)
DC-8-63	Time	-0.327	-0.094	-1.041	-0.137	-1.151	+0.203	—	—
	Fuel	282	159	500	53	728	189	—	—
DC-9-30	Time	—	—	-1.081	-0.058	-1.062	+0.065	-0.991	+0.202
	Fuel	—	—	398	78	516	92	684	25
B-727	Time	—	—	-1.041	+0.070	-1.151	+1.311	-0.878	+0.675
	Fuel	—	—	362	109	616	332	1062	120
B-747	Time	-0.249	+0.753	-1.116	+0.656	-0.974	+1.097	—	—
	Fuel	-53	+271	1110	149	1951	444	—	—
Citation	Time	—	—	-0.698	+0.762	-0.345	+0.656	+0.857	+1.252
	Fuel	—	—	306	444	140	10	135	-1
		FL 450		FL 410		FL 370		FL 330	
Lear Jet	Time	-0-	-1.905	-0-	+0.1742	-1.088	+0.1832	-1.072	+0.277
	Fuel	-19	-18	102	16	185	8	234	14

Time Penalty (minutes) = a t (hours) + b
Fuel Penalty (pounds) = a't (hours) + b'

Table C.7 Controller Communication Time For Overtake Conflict Resolution

Resoltuion	Communication Time (seconds)
Offset	13.5
Speed Reduction	19
Altitude Reclearance	13.5

Additionally, the offset penalty must be assessed. The logic for these procedures is given in Figure C.5.

While offset and altitude reclearance penalties are assessed for "round trip" maneuvers, the aircraft are not generally returned to their original paths unless another conflict occurs.

The controller time required for each conflict is based upon the controller experiments conducted by the FAA at MIT/Lincoln Laboratories (discussed in References 2 and 3). Participating controllers resolved 102 conflicts; in each case, the total controller communication time was recorded. This data was then averaged by conflict type. Table C.7 presents those results relating to overtake conflict resolution.

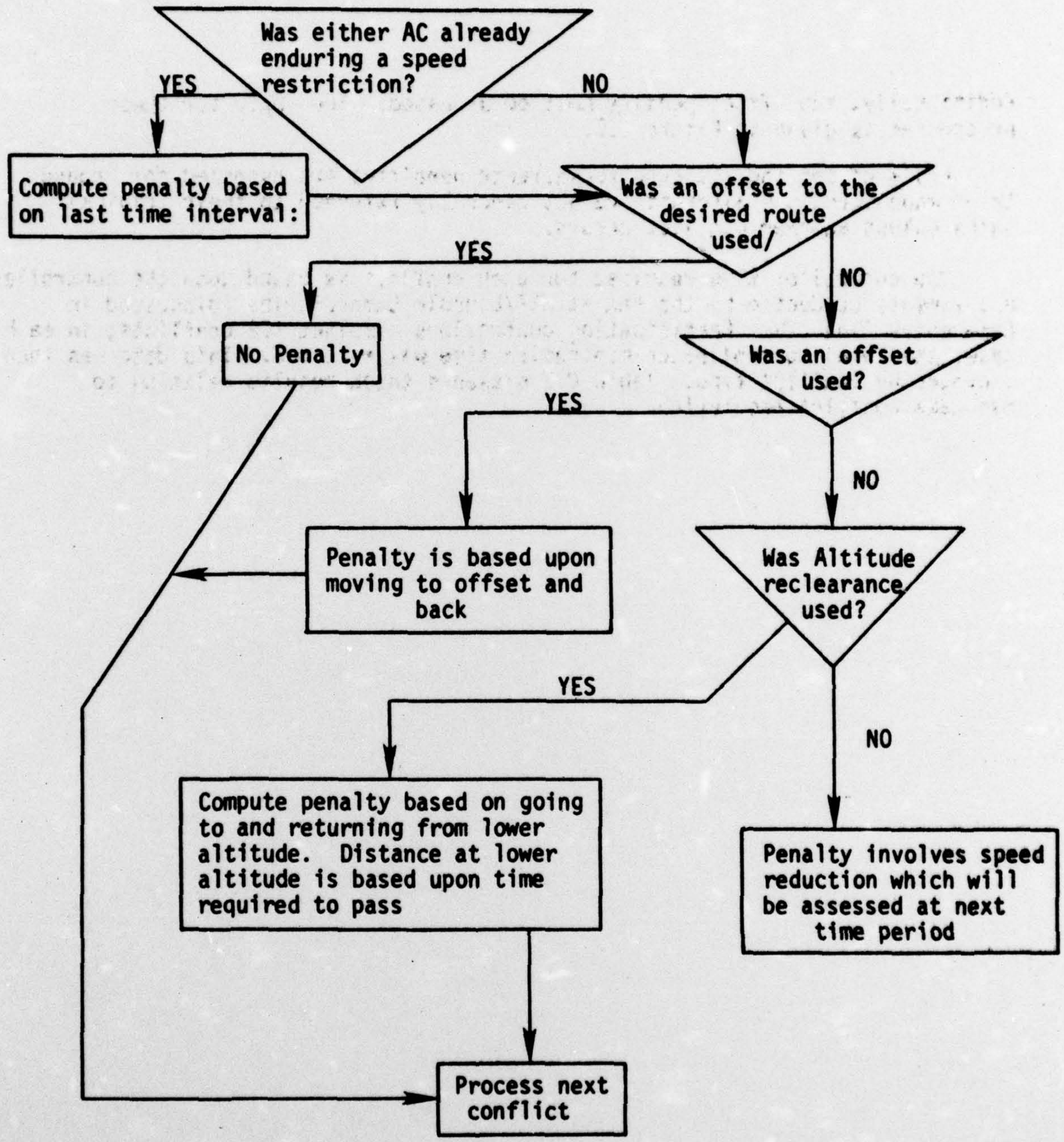


Figure C.5 Penalty Assessment for Eastbound Flights

APPENDIX D

Derivation of Delay Fan Geometry

In Figure D.1:

Let α = magnitude of course change to initiate fan maneuver

w = lateral dimension of fan

ℓ' = longitudinal (along course) dimension of fan

β = magnitude of angle between final fan course and base course

D = aircraft turning diameter

Δx = distance aircraft parallels base course at lateral limit of fan (nominally $\Delta x = 0$)

Let $x_0 = y_0 = 0$

then:

$$x_1 = \ell_1 \cos \frac{\alpha}{2} = D \sin \frac{\alpha}{2} \cos \frac{\alpha}{2} = \frac{D}{2} \sin \alpha$$

$$x_2 = x_1 + S_2 \cos \alpha$$

$$x_3 = x_2 + \ell_3 \cos \delta + \Delta x = x_2 + \Delta x + \ell_3 \cos (\alpha - \frac{\theta}{2})$$

$$= \frac{D}{2} \sin \alpha + S_2 \cos \alpha + D \sin \frac{\theta}{2} \cos (\alpha - \frac{\theta}{2}) + \Delta x$$

$$= S_2 \cos \alpha + D \sin \alpha + \frac{D}{2} \sin \beta + \Delta x$$

$$x_4 = x_3 + S_4 \cos \beta$$

$$x_5 = \ell' = x_4 + \frac{D}{2} \sin \beta \qquad (1)$$

$$y_1 = \ell_1 \sin \frac{\alpha}{2} = D \sin^2 \frac{\alpha}{2} = \frac{D}{2} (1 - \cos \alpha)$$

$$y_1 = y_1 + S_2 \sin \alpha$$

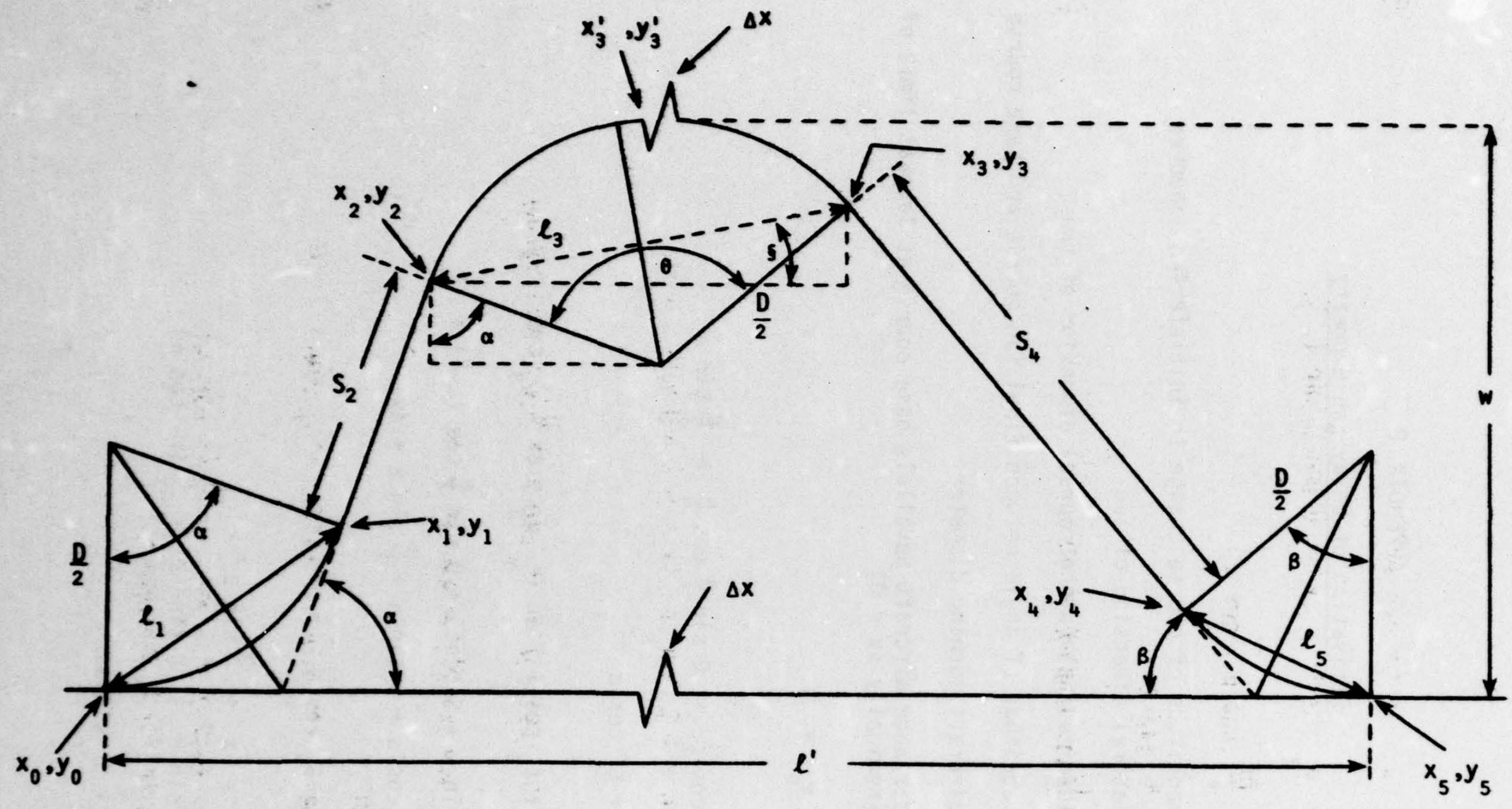


Figure D.1 Delay Fan Geometry

$$y'_3 = w = y_2 + \frac{D}{2}(1 - \cos\alpha) \tag{2}$$

$$y_3 = y_2 + \ell_3 \sin § = y_2 + D \sin\frac{\theta}{2} \sin(\alpha - \frac{\theta}{2})$$

$$= y_2 + \frac{D}{2}(\cos\beta - \cos\alpha)$$

$$y_4 = y_3 - S_4 \sin\beta$$

$$y_5 = y_4 - \frac{D}{2}(1 - \cos\beta) = 0 \tag{3}$$

also:

$$S_1 = \frac{D\,\alpha}{2}$$

$$S_3 = \frac{D\,\theta}{2}$$

$$S_5 = \frac{D\,\beta}{2}$$

from (1):

$$\ell' = D \sin\beta + S_4 \cos\beta + S_2 \cos\alpha + D \sin\alpha + \Delta x \tag{4}$$

from (3):

$$-\frac{D}{2}(1 - \cos\beta) - S_4 \sin\beta + \frac{D}{2}(\cos\beta - \cos\alpha)$$

$$+ S_2 \sin\alpha + \frac{D}{2}(1 - \cos\alpha) = 0$$

simplifying:

$$D\cos\beta - S_4 \sin\beta - D\cos\alpha + S_2 \sin\alpha = 0 \tag{5}$$

from (2):

$$w = \frac{D}{2}(1 - \cos\alpha) + S_2 \sin\alpha + \frac{D}{2}(1 - \cos\alpha)$$

$$w = S_2 \sin\alpha + D\,(1 - \cos\alpha) \tag{6}$$

let $\Delta \ell$ = distance gained in fan maneuver,

then:

$$\ell' + \Delta \ell = S_1 + S_2 + S_3 + \Delta x + S_4 + S_5$$

and,

$$\ell' + \Delta \ell = \frac{D\alpha}{2} + S_2 + \frac{D\,\theta}{2} + \Delta x + S_4 + \frac{D\,\beta}{2} \tag{7}$$

from (6):

$$S_2 = \frac{W - D\,(1 - \cos\alpha)}{\sin\alpha} \tag{8}$$

from (5):

$$S_2 = \frac{D\cos\beta - D\cos\alpha + S_2\sin\alpha}{\sin\beta} \tag{9}$$

from (4):

$$\Delta x = \ell' - D\sin\beta - S_4\cos\beta - S_2\cos\alpha - D\sin\alpha \tag{10}$$

from (7):

$$\Delta \ell = D\alpha + D\beta + S_2 + S_4 + \Delta x - \ell' \tag{11}$$

specify TAS, α, β, ℓ', W

$$D = 6.245 \times 10^{-5}\,(TAS)^2$$

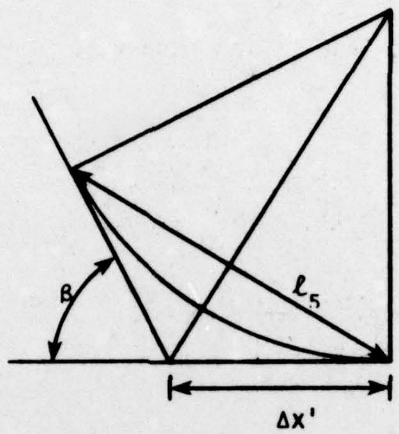
$$S_2 = \frac{W - D\,(1 - \cos\alpha)}{\sin\alpha}$$

$$S_4 = \frac{S_2\sin\alpha - D\cos\alpha + D\cos\beta}{\sin\beta}$$

$$\Delta x = \ell' - D\sin\alpha - D\sin\beta - S_2\cos\alpha - S_4\cos\beta$$

$$\Delta \ell = S_2 + S_4 + \Delta x - \ell' + D\,(\alpha + \beta)$$

Final Leg of fan on heading of next leg:



$$\Delta x' = \frac{\ell_5}{\cos\frac{\beta}{2}} = \frac{1}{2}\frac{D\sin\frac{\beta}{2}}{\cos\frac{\beta}{2}}$$

$$\Delta x' = \frac{D}{2}\tan\frac{\beta}{2}$$

$$\Delta\ell' = \Delta\ell - S_5 + \Delta x'\cos\beta + \Delta x$$

$$\Delta\ell' = \Delta\ell - D\beta + \Delta x'\cos\beta$$

"S" turn delay maneuver:

$$\beta_1 = \alpha_2$$

$$\Delta x'' = \frac{D}{2}\tan\frac{\alpha}{2}$$

$$\Delta\ell'' = \Delta\ell - S_1 + \Delta x''\cos\alpha + \Delta x''$$

$$\Delta\ell'' = \Delta\ell - D\alpha + \Delta x''\cos\alpha$$

$$\Delta\ell_s = \Delta\ell_1' + \Delta\ell_2''$$

$$\ell'_{s_{min.}} = \ell_1' - \Delta x_1 - \Delta x_1' + \ell_2' - \Delta x_2 - \Delta x_2'$$

*U.S. GOVERNMENT PRINTING OFFICE: 1977 726-119/884 1-3